BUCKNELL UNIVERSITY LIBRARY
MAR 2 1955
LEWISBURG, PA.

Journal

of

THE ROYAL AERONAUTICAL SOCIETY

FEBRUARY 1955

CONTENTS

NOTICES

THE FIRST CAYLEY MEMORIAL LECTURE
SIR GEORGE CAYLEY, Bart.,
THE FATHER OF BRITISH AERONAUTICS
J. LAURENCE PRITCHARD

MINIMUM WEIGHT DESIGN OF THIN-WALLED CELLS IN TORSION — V. CADAMBE and S. KRISHNAN

REHEAT FOR GAS TURBINES — J. L. EDWARDS

TECHNICAL NOTES

Buckling and Vibration of Isosceles Triangular Plates having the Two Equal Edges Clamped and the Other Edge Simply-Supported—HUGH L. COX and BERTRAM KLEIN. Generalised Stress-Strain Data for Aluminium Alloys and certain other Materials—ANTHONY J. BARRETT and MAUREEN E. MICHAEL.

THE LIBRARY — REVIEWS — REPORTS

TEN SHILLINGS MONTHLY

LONDON
4 HAMILTON PLACE W1

The LION ... the latest and greatest ACTUATOR by Plessey

Working load.. normal 2,000 lbs., max. 2,500 lbs.	
Static load	10,000 lbs.
Stroke	4 inches
Time for 4-inch stroke	10 secs.
Rating	1½ minutes
Weight	15¼ lbs.
Working Voltage	92/115 volts D.C.

PUMPS • VALVES • CARTRIDGE STARTERS • PRE-FORMED WIRING SYSTEMS • ELECTRIC ACTUATORS

THE PLESSEY COMPANY LIMITED • ILFORD • ESSEX

A41

Journal of

THE ROYAL AERONAUTICAL SOCIETY

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

PUBLISHED MONTHLY AT

4 HAMILTON PLACE, LONDON, W.1

Telephone: Grosvenor 3515-9 *Telegrams*: Didaskalos, Audley, London

SUBSCRIPTIONS: £6 6s. 0d. PER ANNUM, POST FREE. SINGLE COPIES: 10s. 6d., POST FREE.

VOLUME 59 FEBRUARY 1955 NUMBER 530

CONTENTS

PAGE

Notices VII

Nomination of Candidates for Council—Nominations for Fellowship of the Society—New Year's Honours List, 1955—Association of British Aero Clubs and Centres—Lecture, 1955 Brancker Memorial Lecture—News of Members—Honours to Members—Graduates' and Students' Section, Annual General Meeting—Visit—Institution of Mechanical Engineers, Clayton Lecture—Diary—Elections—Changes of Address—Annual Subscriptions—Journal Binding.

The First Cayley Memorial Lecture—
Sir George Cayley, Bart.,
The Father of British Aeronautics — J. LAURENCE PRITCHARD — 79

Minimum Weight Design of Thin-walled Cells in Torsion — V. CADAMBE and S. KRISHNAN — 120

Reheat for Gas Turbines — J. L. EDWARDS — 127

Technical Notes 151

Buckling and Vibration of Isosceles Triangular Plates having the Two Equal Edges Clamped and the Other Edge Simply-Supported—HUGH L. COX and BERTRAM KLEIN. Generalised Stress-Strain Data for Aluminium Alloys and certain other Materials—ANTHONY J. BARRETT and MAUREEN E. MICHAEL.

The Library 159

REVIEWS:—Massbalancing of Aircraft Control Surfaces—Further Outlook—Limitation of Liabilities in International Air Law—Cheshire, V.C.—Definitions for Use in Mechanical Engineering.

ADDITIONS TO THE LIBRARY. REPORTS.

All communications for publication in, and advertisements for, the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., A.F.I.A.S., A.F.R.Ae.S.*

None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

PRINTED BY THE LEWES PRESS (WIGHTMAN & CO. LTD.), LEWES, SUSSEX, ENGLAND, AND PUBLISHED BY THE ROYAL AERONAUTICAL SOCIETY, 4 HAMILTON PLACE, LONDON, W.1, ENGLAND

The Royal Aeronautical Society

(Founded 1866)

PATRON

HER MAJESTY THE QUEEN

COUNCIL 1954—1955

PRESIDENT

SIR SYDNEY CAMM, C.B.E., F.R.Ae.S.

PAST PRESIDENTS

SIR WILLIAM S. FARREN, C.B., M.B.E., M.A., F.R.S., Hon.F.I.A.S., F.R.Ae.S.
G. H. DOWTY, F.I.A.S., F.R.Ae.S.
MAJOR F. B. HALFORD, C.B.E., F.R.Ae.S.

VICE-PRESIDENTS

G. R. EDWARDS, C.B.E., B.Sc., F.R.Ae.S.
A. G. ELLIOTT, C.B.E., F.R.S.A., F.R.Ae.S.
P. G. MASEFIELD, M.A., F.I.A.S., F.R.Ae.S.

ORDINARY MEMBERS

AIR COMMODORE F. R. BANKS, C.B., O.B.E., M.I.Mech.E., F.R.Ae.S.
PROFESSOR A. D. BAXTER, M.Eng., M.I.Mech.E., F.R.Ae.S.
SIR JOHN S. BUCHANAN, C.B.E., A.M.I.Mech.E., F.R.Ae.S.
MAJOR G. P. BULMAN, C.B.E., B.Sc., F.R.Ae.S.
PROFESSOR A. R. COLLAR, M.A., D.Sc. A.F.I.A.S., F.R.Ae.S.
E. B. DOVE, A.R.Ae.S.
PROFESSOR W. J. DUNCAN, C.B.E., D.Sc.(Eng.), F.R.S., M.I.Mech.E., F.R.Ae.S.
SIR HARRY M. GARNER, K.B.E., C.B., M.A., F.R.Ae.S.
SIR ARNOLD HALL, M.A., F.R.S., F.R.Ae.S.
P. A. HEARNE, D.C.Ae., D.L.C., Grad.R.Ae.S.
E. T. JONES, C.B., O.B.E., M.Eng., F.R.Ae.S.
DR. E. S. MOULT, B.Sc.(Eng.), M.I.Mech.E., F.R.Ae.S.
CAPT. J. L. PRITCHARD, C.B.E., Hon.F.I.A.S., Hon.F.R.Ae.S.
N. E. ROWE, C.B.E., B.Sc., D.I.C., M.I.Mech.E., F.I.A.S., F.R.Ae.S.
B. S. SHENSTONE, M.A.Sc., A.F.I.A.S., F.R.Ae.S.
W. TYE, O.B.E., B.Sc., F.R.Ae.S.
DR. P. B. WALKER, M.A., F.R.Ae.S.

OFFICERS

Honorary Treasurer: MAJOR G. P. BULMAN, C.B.E., B.Sc., F.R.Ae.S.
Solicitor: L. A. WINGFIELD, M.C., D.F.C., A.R.Ae.S.
Secretary: DR. A. M. BALLANTYNE, T.D., A.F.I.A.S., A.F.R.Ae.S.

NOTICES

An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

Nomination of Candidates for Council

The following is an extract from the By-Laws:—

"The Twenty-one ordinary members (of the Council) shall be nominated and elected from among the members of the Society. At the date of their election at least ten shall be Fellows, and one at least shall be in each of the following classes: Associate Fellow, Associate and Graduate.

"Of the ordinary members of the Council, that number necessary to create seven vacancies shall retire annually. The retiring members shall be those with the longest service since their last election but they shall be eligible for re-election.

"Nominations of candidates for election to the Council must be received by the Secretary not later than 10th April in each year and shall include statements in writing by the candidates that they are willing to serve. The nomination forms shall be signed by one proposer and two seconders, all of whom shall be Voters."

Nomination forms may be obtained on application to the Secretary.

Graduates' and Students' Section

Annual General Meeting

The Annual General Meeting of the Section will be held in the Offices of the Society, 4 Hamilton Place, W.1, on Wednesday 9th March 1955, at 7.0 p.m. Light refreshments will be served from 6.30 p.m. to 7.0 p.m.

The meeting will be followed by a film show, admission to which will be by ticket only.

Agenda

1. To consider and approve the Minutes of the previous Annual General Meeting.
2. To consider any business arising from these Minutes.
3. To receive the report of the Committee on the activities of the Committee and the Section during the past year.
4. To make recommendations to Council on the names of the representatives of the Section to serve on the Committee for the year 1955-56.
5. To receive the Rules for the administration of the Section.
6. To discuss the future activities of the Section.
7. To consider any other matters connected with the affairs of the Section.

Nominations for the Section representatives on the Committee should be sent to the Hon. Secretary before the 7th March, or may be handed in at the meeting. They must be signed by the candidate, proposer and seconder, who must all be Graduates or Students. The number of vacancies to be filled is nine and, if the nominations exceed this number, a ballot will be held at the meeting.

The successful candidates' names will be subject to confirmation by Council.

Members are reminded that it is desirable for the Committee to be representative of as many firms and Colleges as possible.

Alan E. Brock,
Hon. Secretary.

77 Broughton Road
Thornton Heath, Surrey.

Nominations for Fellowship of the Society

The attention of Members is drawn to the following extract from the Society's By-Laws:—

"Fellows shall comprise every person who on the 30th day of January 1950 was on the Register as a Fellow of the Society; and every person thereafter awarded the honour of Fellowship.

"Elections to Fellowship will be made annually by the Council and will be announced at the Annual General Meeting of the Society. Nominations will be initiated by the members of the Council or by any four Fellows of the Society. It is the duty of the Council to see that the honour is awarded only to persons who have attained a considerable degree of technical eminence in the profession of aeronautics."

From this, it will be seen that any four Fellows may nominate a suitable candidate for Fellowship.

The date when nominations must be received by the Secretary has been extended to 28th February 1955.

Honours to Members

Major D. Lester Gardner (*Honorary Fellow*) and Sir Richard Southwell (*Fellow*) have been elected Honorary Fellows of the Institute of the Aeronautical Sciences for the year 1954.

Dr. William Jones (*Fellow*) is one of six new Fellows elected by the Institute.

Dr. Theodore von Kármán (*Honorary Fellow*) has been awarded the Wright Brothers Memorial Trophy (awarded for public service of enduring value to aviation in the United States) for his "outstanding achievements in supersonic research and jet propulsion."

New Year Honours List 1955

The following members were included in the New Year Honours List:—

Knight Batchelor
Rear-Admiral M. S. Slattery (*Fellow*)

Order of the Bath (C.B.)
Mr. W. R. McGaw (*Associate Fellow*)

Order of the British Empire

C.B.E.—Mr. B. Lampard-Vachell (*Associate Fellow*)
Professor G. Temple (*Fellow*)

O.B.E.—Professor L. Howarth (*Associate Fellow*)
Mr. E. L. Ripley (*Associate Fellow*)
Mr. W. H. Yoxall (*Associate Fellow*)

M.B.E.—Mr. S. A. Cooper (*Associate*)

Association of British Aero Clubs and Centres

H.R.H. The Duke of Edinburgh (*Honorary Fellow*) has become the Patron of the Association of British Aero Clubs and Centres.

Lecture—1955 Brancker Memorial Lecture

The 1955 Brancker Memorial Lecture of the Institute of Transport will take place at 5.45 p.m. on Monday 14th February at the Jarvis Hall (R.I.B.A.), 66 Portland Place, London, W.1. The lecturer will be Sir Arnold Hall, Director, Royal Aircraft Establishment, who will speak on "The influence on civil aviation of some current researches." Members of the Society are invited to attend.

Diary

LONDON

10th **February**
MAIN LECTURE AT ISLE OF WIGHT BRANCH—Prospects and Problems of Rocket Propulsion for Aircraft. Professor A. D. Baxter. Saunders-Roe Club House, Church Path, E. Cowes. 7 p.m.

15th February
GRADUATES' AND STUDENTS' SECTION—Discussion: Is Post-graduate Study Abroad Worthwhile? Chairman, Sir Arnold Hall. 4 Hamilton Place, W.1. 7.30 p.m.

17th February
SECTION LECTURE—Problems Associated with Stress Concentration. H. L. Cox. 4 Hamilton Place, W.1. 7 p.m.

19th February
GRADUATES' AND STUDENTS' SECTION—Visit to the Guinness Brewery at Park Royal, London. 2.15 p.m.

1st **March**
SECTION LECTURE—The Scientific Approach and Research in Aircraft Production. Professor J. V. Connolly. 4 Hamilton Place, W.1. 7 p.m.

9th March
GRADUATES' AND STUDENTS' SECTION—Annual General Meeting and Film Show—The Society Overseas. Dr. A. M. Ballantyne. 4 Hamilton Place, W.1. **7 p.m.**

10th March
MAIN LECTURE AT PRESTON BRANCH—Structural Safety. Professor A. G. Pugsley, O.B.E. The Bull and Royal Hotel, Preston. 7.30 p.m.

15th March
SECTION LECTURE—The Production of Large Forgings. C. Smith and J. Crowther. 4 Hamilton Place, W.1. 7 p.m.

17th March
EIGHTH LOUIS BLERIOT LECTURE, LONDON—Making Aeroplanes Independent of Runways. Monsieur Georges Hereil, President, Director-General, S.N.C.A.S.E. Institution of Mechanical Engineers, 1 Birdcage Walk, S.W.1. 6 p.m. (Tea 5.30 p.m.)

24th March
MAIN LECTURE—Analogue Computing Applied to Aeronautical Problems. K. V. Diprose. Institution of Mechanical Engineers, 1 Birdcage Walk, S.W.1. 6 p.m. (Tea 5.30 p.m.)

29th March
GRADUATES' AND STUDENTS' SECTION—Atomic Energy. Professor J. Rotblat. 4 Hamilton Place, W.1. 7.30 p.m.

31st March
SECTION LECTURE—Application of Aerial Survey to the Economic Development of a Country. T. D. Weatherhead, O.B.E. 4 Hamilton Place, W.1. 7 p.m.

BRANCHES

10th **February**
Isle of Wight—Main Lecture—Prospects and Problems of Rocket Propulsion for Aircraft. Professor A. D. Baxter. Saunders-Roe Club House, Church Path, E. Cowes. 7 p.m.

11th February
Glasgow—Operation and Servicing of Jet Engines. J. R. Nutter. Royal Technical College, Glasgow. 7.30 p.m.

14th February
Bristol—Junior Members' Papers Competition. Conference Room, Bristol Aeroplane Co., Filton House. 6 p.m.
Halton—Electronic Equipment. Branch Hut, R.A.F., Halton. 6.45 p.m.

16th February
Manchester—The Scientific Approach to Production Problems. Professor J. V. Connolly. Reynolds Hall, College of Technology, Manchester. 7.30 p.m.

17th February
Yeovil—Fatigue. Dr. P. B. Walker. Park School, Park Road (off Princes Street), Yeovil. 7.30 p.m.

18th February (previously arranged on 11th February)
Birmingham—The Development of Reheat. J. L. Edwards. Birmingham Chamber of Commerce, New Street, Birmingham. 7.30 p.m.

21st February
Halton—Branch Night. Aircraft Operations in the Arctic. Major Webb, U.S.A.A.F. Branch Hut, R.A.F., Halton. 6.45 p.m.
Henlow—Aircraft Production. Professor J. V. Connolly. Building No. 62, R.A.F. Technical College, Henlow. 7.30 p.m.

22nd February
Belfast—Trends of Engine Development. Dr. S. G. Hooker. Kerr Room, Kensington Hotel, Belfast. 7 p.m.
Bristol—Some Aspects of the Work of an Aircraft Testing Establishment. Handel Davies. Conference Room, Bristol Aeroplane Co., Filton House. 6 p.m.

23rd February
Preston—Lecture. Harris Institute, Preston. 7.30 p.m.
Southampton—Branch Prize Papers. Institute of Education, University of Southampton. 7 p.m.
Weybridge—R. K. Pierson Memorial Lecture. W. E. W. Petter, C.B.E. Vickers-Armstrongs Ltd., Weybridge. 6 p.m.

25th February
Belfast—Annual Dance. Malone House (Barnett's Park), Belfast. 9 p.m.-2 a.m.

1st **March**
Boscombe Down—Recent Developments in Gliding. A. H. Yates. Main Dining Hall, Airmen's Mess, A. and A.E.E., Boscombe Down. 5.30 p.m.

2nd March
Brough—Pilot's Limitations in Aircraft Design. W. Cdr. H. P. Ruffell Smith. Lecture Hall, Yorkshire Electricity Board, Ferensway, Hull. 7.30 p.m.
Chester—Members' Lecturettes. The Grosvenor Hotel, Chester. 7.30 p.m.
Gloucester—Aircraft Carriers. J. Foster Petree. The Wheatstone Hall, Brunswick Road, Gloucester. 7.30 p.m.

7th March
Glasgow—Design Criteria for Fatigue of Wings. Dr. P. B. Walker. Royal Technical College, Glasgow. 7.30 p.m.
Halton—Films. How an Aeroplane Flies. Branch Hut, R.A.F., Halton. 6.45 p.m.
Henlow—Student Members' Lectures. Building No. 62, R.A.F. Technical College, Henlow. 7.30 p.m.

8th March
Bristol—Second Barnwell Memorial Lecture. W. Tye, O.B.E. Conference Room, Bristol Aeroplane Co., Filton House. 7 p.m.

10th March
Preston—Main Lecture—Structural Safety. Professor A. G. Pugsley, O.B.E. The Bull and Royal Hotel. 7.30 p.m.
Yeovil—Cabin Air Conditioning. Park School, Park Road (off Princes Street), Yeovil. 7.30 p.m.

12th March
Birmingham—Annual Dinner.

14th March
Halton—Cabin Pressurisation. F. W. Michael. Branch Hut, R.A.F., Halton. 6.45 p.m.

15th March
Belfast—Aerial Photography. Charles Brown. Kerr Room, Kensington Hotel, Belfast. 7 p.m.
Manchester—Helicopters. G. S. Hislop. Reynolds Hall, College of Technology, Manchester. 7.30 p.m.

16th March
Southampton—The A.R.A. Wind Tunnel. R. Hills. Institute of Education, University of Southampton. 7 p.m.
Weybridge—Modern Motor Vehicle Production Methods with Special Reference to Jaguar Cars. J. Silver. Vickers-Armstrongs Ltd., Weybridge. 6 p.m.

18th March
Birmingham—Trends in Development of Aircraft Electrical and Starting Systems. R. H. Woodall. Birmingham Chamber of Commerce, New Street, Birmingham. 7.30 p.m.

21st March

Halton—Branch Night. Films and Discussion. Branch Hut, R.A.F., Halton. 6.45 p.m.

Henlow—Film. Hell's Angels. Building No. 62, R.A.F. Technical College, Henlow. 7.30 p.m.

Yeovil—Production Problems on Helicopters. D. C. Collins. Park School, Park Road (off Princes Street), Yeovil. 7.30 p.m.

22nd March

Bristol—Some of the Problems of Bomber Design. D. Keith-Lucas. Conference Room, Bristol Aeroplane Co., Filton House. 6 p.m.

23rd March

Cheltenham—Some Problems of Bomber Design. D. Keith-Lucas. St. Mary's College, Cheltenham. 7.30 p.m.

Luton—Annual General Meeting. Staff Canteen. D. Napier & Son Ltd., Luton Airport. 7.30 p.m.

25th March

Southampton—Annual Dance.

28th March

Halton—Junior Members' Night. Lecture and Discussion. Branch Hut, R.A.F., Halton. 6.45 p.m.

30th March

Brough—Annual General Meeting and Film Show. Yorkshire Electricity Board, Ferensway, Hull. 7.30 p.m.

5th **April**

Boscombe Down—The Light Fighter. W. E. W. Petter, C.B.E. Main Dining Hall, Airmen's Mess, A. and A.E.E., Boscombe Down. 5.30 p.m.

Glasgow—The Twin Pioneer: Design, Production and Test Flying. T. B. Lyon, J. Hislop and N. J. Capper. Royal Technical College, Glasgow. 7.30 p.m.

6th April

Chester—Operation of Jet-Engined Aircraft. The Grosvenor Hotel, Chester. 7.30 p.m.

Luton—Aerial Photography. Russell Adams. Staff Canteen, D. Napier & Son Ltd., Luton Airport.

Weybridge—Some Maintenance Aspects of Viscount Operation. E. R. Major. Vickers-Armstrongs Ltd., Weybridge. 6 p.m.

News of Members

K. V. Bonney (*Associate*) has been appointed Project Engineer with the Research Department of Handley Page Ltd.

Captain D. Brice (*Associate*) has been appointed Managing Director of Sir Henry Lunn Ltd.

E. L. Carlisle (*Associate Fellow*) has taken up an appointment as Chief Engineer of the Engine Division of Field Aircraft Services Limited.

P. K. Digby (*Associate Fellow*) has been appointed Staff Tutor at Birmingham University in the subjects of Planning, Production and Management Controls and Procedural Analysis.

D. L. Evans (*Associate Fellow*) has been appointed Head of the Engineering Department of the Rochdale Municipal Technical College.

S. F. Follett (*Associate Fellow*) has been promoted to Chief Scientific Officer, and has been appointed Principal Director of Equipment and Research Development (Air), Ministry of Supply.

M. A. Glasspole (*Associate Fellow*), formerly of the Technical Staff at A. V. Roe & Co. Ltd., Manchester, has now joined H. M. Hobson & Co. Ltd., Wolverhampton, as Senior Designer.

F. Hamilton (*Associate Fellow*) is now Assistant Chief Designer (Christchurch) at The de Havilland Aircraft Co. Ltd.

S. Kugler (*Associate Fellow*) has taken up an appointment as Senior Development Engineer with British Oxygen Engineering Ltd.

J. D. Mann (*Graduate*), previously employed by Blackburn and General Aircraft Co., has now taken a post as Technical Assistant, Central African Airways Corporation, in S. Rhodesia.

E. S. Pearse (*Associate Fellow*) has relinquished his position as Works Manager, and has been appointed Works Director of Quickfit & Quartz Limited, Stone, Staffs.

A. G. Peters (*Associate*) has been appointed Assistant Chief Designer (Hatfield) of The de Havilland Aircraft Co. Ltd.

G. A. G. Saywell (*Associate*) has taken up an appointment with the Hoffmann Manufacturing Co., Chelmsford, as Chief Inspector.

W. A. Tamblin (*Fellow*) has been appointed Chief Designer (Christchurch) of The de Havilland Aircraft Co. Ltd.

R. G. Thorne (*Associate Fellow*) has been elected the first Chairman of the Documentation Committee of AGARD.

R. E. Tollerfield (*Associate*) is now the Chief Inspector for Attewell Engineering Co., Bath Aircraft Tool Makers.

C. T. Wilkins (*Fellow*) has become Chief Designer at The de Havilland Aircraft Co. Ltd. (Hatfield).

P. J. Wingham (*Associate Fellow*) has joined the Weapons Research Division of A. V. Roe & Co. Ltd., at Woodford, Cheshire.

Graduates' and Students' Section—Visit

A visit has been arranged to the Guinness Brewery at Park Royal, London, for Saturday 19th February 1955 at 2.15 p.m. Applications for this visit should be made immediately to the Hon. Visits Secretary, Mr. P. D. Stewart, 217 High Road, East Finchley, London, N.2.

Elections

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

James Ormond Bolton
Kenneth Richard Brine (*from Graduate*)
B. R. Sampath Kumaran
Robert James Ross
Alec George Sollis (*from Associate*)
Mohammed Abd El Meguid M. Zimaity (*from Graduate*)

Associates

Ernest Edgar John Horney (*from Graduate*)
Christoffel Hendrik Oberholzer
Stanley Webster

Graduate

Gwynne Morris Jones

Students

Brian Brimelow
David John McNally

Companion

Bernard Bernard

Institution of Mechanical Engineers

Clayton Lecture

Dr. I. Sikorsky, who has been awarded the 1955 James Watt International Medal by the Institution of Mechanical Engineers, is to give the James Clayton Lecture on the 29th April 1955. All members of the Society are welcome to attend this Lecture, which will be held at the Institution of Mechanical Engineers, 1 Birdcage Walk, S.W.1, at 5.30 p.m.

Annual Subscriptions

Members are reminded that their annual subscriptions became due on 1st January 1955. The rates are:—

	Home			Abroad		
	£	s.	d.	£	s.	d.
Fellows	5	5	0	4	4	0
Associate Fellows	4	4	0	3	3	0
*Associates	3	3	0	3	3	0
Graduates (aged under 26)	2	2	0	2	2	0
Graduates (aged 26 and over)	2	12	6	2	12	6
Students (aged under 21)	1	1	0	1	1	0
Students (aged 21 and over)	1	11	6	1	11	6
Companions	3	3	0	3	3	0
Founder Members	2	2	0	2	2	0

* Any Associate elected before 1st October 1947 may, if he wishes, elect not to receive the JOURNAL, and in this case his subscription will be reduced by £1 1s. 0d. to £2 2s. 0d.

It will avoid delay and confusion if members, when sending remittances for subscriptions, will state their names clearly and give their addresses and grades of membership. Remittances should be made payable to the Royal Aeronautical Society.

Journal Binding

Permanent Binding

The new prices for permanent binding of Journals are:

1954 Volume (including packing and postage)	18s. 6d.
1953 Volume (including packing and postage)	19s. 0d.
Previous Volumes (including packing and postage)	18s. 0d.

Journals, with a note of the name and address of the sender, should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Self-Binder Cases

Self-Binder cases of the "Easibind" type to hold 12 Journals (cost 11s. 6d. each) are available from the offices of the Society.

Changes of address

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters).	New address (in block letters).
Grade of Membership.	Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the JOURNAL for the following month.

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 59 FEBRUARY 1955 NUMBER 530

THE FIRST CAYLEY MEMORIAL LECTURE

The 922nd Lecture to be read before the Society was the 14th Main Lecture to be held at a Branch and was also the First Cayley Memorial Lecture. Entitled "Sir George Cayley, Bart., The Father of British Aeronautics," it was given by Captain J. L. Pritchard, C.B.E., Hon.F.R.Ae.S., Hon.F.I.A.S., under the auspices of the Brough Branch of the Society at Hull on 4th November 1954. Mr. Robert Blackburn, O.B.E., Hon.F.R.Ae.S., Chairman of the Brough Branch, presided at the meeting, with Mr. A. G. Elliott, C.B.E., F.R.Ae.S., Vice-President of the Society, deputising for the President.

MR. ROBERT BLACKBURN, opening the meeting: It is my prime duty tonight to welcome our distinguished visitors to the inaugural Sir George Cayley Memorial Lecture. This memorial lecture is, I feel, closely identified with myself, as the Brough Branch has acted on a suggestion I made at the 50th Anniversary of Powered Flight Dinner in Hull last December.

I have always felt a great thrill in my mind from those early days of aviation when I heard of Sir George Cayley and some of his exploits and his work in the early 1800's is acknowledged to be the very foundation of aviation as we know it today. A memorial lecture linked to his name will keep alive the realisation of the true worth of the life and work of a great Yorkshireman.

Far be it from me to intrude upon our very distinguished lecturer's preserves by recounting any of the exploits of this Yorkshire-born pioneer. Suffice it to say that his astonishing foresight is best summed up in the imaginative phrase, "There is an uninterrupted, navigable ocean which comes to the threshold of everyman's door."

Tonight we have, unfortunately, been deprived of the presence of our President, Sir Sydney Camm, who is the guest of honour at another annual dinner. However, I can think of no more worthy deputy than Mr. A. G. Elliott, who is joint Managing Director and Chief Engineer of the great company of Rolls-Royce. To have a director of such a company present at this outstanding date in the Brough Branch calendar sets the seal on this occasion.

We are also pleased to see with us tonight the Secretary of the Main Society, Dr. A. M. Ballantyne, Mr. D. C. Smith and other officers of the Society. The Chairman of the Branches Committee, Mr. N. E. Rowe, my colleague, is also with us and everyone in the Brough Branch is delighted that he is to become the President of the Society in 1955. In addition we have representatives from some of the branches. I welcome everyone tonight more particularly because in this winter session the Brough Branch is celebrating its 25th anniversary.

MR. A. G. ELLIOTT, taking the Chair: I am deputising for your President, Sir Sydney Camm, and I feel very happy and proud to be with you tonight, particularly as it is a good many years since I visited Brough.

There are many here who have known and grown up with Captain Pritchard over the years, and know just as much as I about his history and his very long association with the Royal Aeronautical Society. But I am sure some of the younger members are not so familiar with the details of his career.

Captain Pritchard was educated at Dulwich College and Christ's College, Cambridge. After coming down from Cambridge he entered Fleet Street in 1908, where he wrote on most subjects, including aviation. Early in the First World War he joined the Royal Fusiliers, and in 1916 transferred to the Royal Naval Air Service. In 1918 he transferred to the Air Ministry and is therefore one of the few people who served in the three Services.

In 1919 Captain Pritchard became Editor of the *Journal* of the Society, an appointment which he held until 1946. In 1925, at the request of the Council, he took over the duties of Secretary of the Society in an honorary capacity, and took over the full duties of Secretary in 1927, from which he retired in 1951.

In his twenty-five years of service he has seen the membership grow from 700 to over 7,000; the subscription income rise from £1,900 to £21,000; the formation of the Branches; Divisions in Australia, New Zealand and South Africa; the inauguration of an Endowment Fund, and the acquisition by the Society of a house of its own for the first time in its history.

The growth of the Society, its present wide influence and high reputation; the range of its activities from the issue of monographs and data sheets to the Anglo-American Conferences, and Annual Flying Garden Parties, owes much to the work of Laurence Pritchard over the years—and to his great personal qualities.

Following the Lecture, Captain Pritchard was thanked by Mr. Elliott and Mr. Blackburn and was presented by Mr. Blackburn with a silver salver, suitably engraved.

MR. ELLIOTT: We have listened tonight to a most interesting lecture in which Captain Pritchard has given us a most comprehensive, complete review of that remarkable man, Sir George Cayley.

It seems to me that he was a most unusual combination of what might be called an amateur scientist and theoretician combined with an experimentalist having a very practical outlook but with limited resources at his command. He made some most far seeing experiments, and what was denied him were resources which would have carried him far beyond the point that he did reach.

He originated some remarkable principles. For example, the hot air engine. Then there was his caterpillar engine. It is a great pity that there were not some good engine manufacturers in those days. It would certainly have led to the development of that vehicle and its very complete application to our needs today.

Again there was the skin cooling on aerodynamic surfaces, which was used on the Supermarine Schneider Cup winner. And there was the Cayley landing wheel, which really anticipated the principles of the wire spoked bicycle and motor car wheel of today. All of these were most remarkable developments from an extremely original mind.

One other thing which impressed me very much indeed was that Cayley said the main object of aeroplane flight was speed—which was extraordinarily true and is true today. The civil operator of aircraft is selling speed, and when you go in an aeroplane you go in it because it is going to get you so much more quickly on your way that you will

be glad when you get there and get out! Nevertheless you and others will continue to travel by the fastest air lines because it is speed you are buying.

I was very impressed by the "converter plane" because there, it seems to me, you have the conception of a machine which goes beyond the sort of aircraft we are actually using today and does not require a mile long concrete runway to get off the ground.

MR. BLACKBURN: My duty is a happy one, in proposing a vote of thanks to our lecturer tonight. In unravelling all the exploits and work of that wonderful man he has given me something, which, although I know his name and great work, has come as a revelation of what he actually did. To Laurence Pritchard who collected all the knowledge of that man's work I give great credit.

You, Laurence Pritchard, in inaugurating a series of lectures which we trust will do much to foster the study of aeronautics in this pioneering country, have earned our deep gratitude. I have here a small memento of this special occasion, presented to you by the Brough Branch of the Society, to mark our appreciation. It gives me great pleasure to present it to you.

CAPTAIN PRITCHARD: I am sometimes glad when my voice cracks because you will not put it down to the wrong reason. I did not think I should finish this lecture, and if I had known what was going on I certainly should not have finished it.

I thank you very much for all the nice things which have been said about me.

I was sorry to hear Mr. Elliott say that speed is the only thing you have to sell. I have always said, and will go on saying, that what the aeroplane is selling is not speed at all—but no miles per hour. You have too much power, thanks to these big engine people, and you are pulling everything through the sky and are not flying as we used to fly in the early days. The craze for speed was fostered by the big engine people who were selling power, but I notice when they go to America or anywhere else they all go by the *Queen Mary*.

Over the years in the Society I have tried many times to do something which I think should be done. A man has very little honour in his own country. Cayley for the first time has had honour in his own country. The Royal Aeronautical Society should, I think, honour its own people—Cayley is one of them—Stringfellow is another and in later years, Lanchester. These people should be honoured by this Society; whether it is a medal to be given or a paper to be read, their names should be enshrined in some way by the Society.

Brearey, the first Honorary Secretary, was a Yorkshireman and was the man who got this Society going. He made flying models, some of which flew round a room. He used to lecture in halls and many other places. He used to lecture in rooms of this size—this was in 1870—and he could get real models to fly round the room and come back to him. He did this all over the country and not just once. He lived to a great age and I hope I may emulate him.

N. E. ROWE: We have heard about a very great Yorkshireman who was extremely advanced in his views, and the talk has been given to us by a man who has a great sense of history, and it has been given in a hall in Yorkshire to a Branch of the Royal Aeronautical Society.

I hope that this occasion will be the highlight in the Branch year in future, as it is intended to be in other branches where named lectures have been started.

We have seen the impact of a great amateur. The amateur comes in and asks the simple searching questions that are so difficult to answer. I think the Branches of our Society have introduced a part of that amateur element and for that reason they are excellent, and I would like to see all the Branches extend as far as they can, their membership to those interested in aviation but who are not professionally engaged. I am sure it will be of the greatest value and practical help to the Society as a whole.

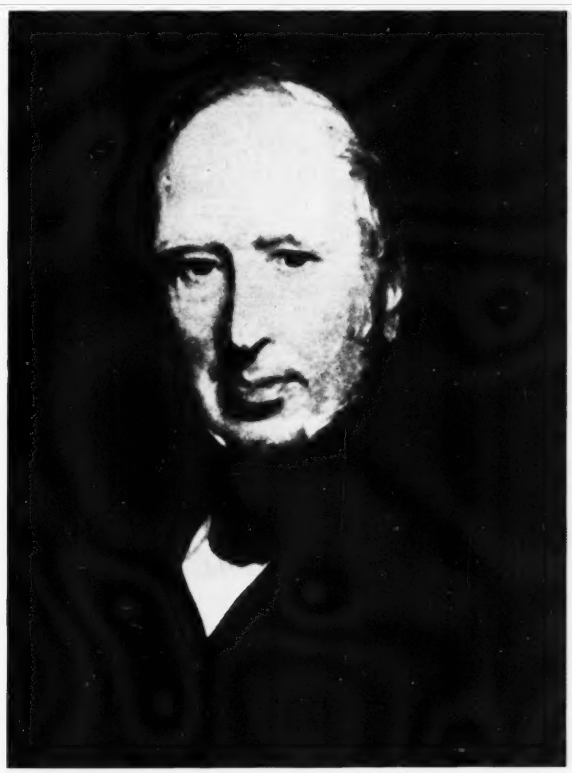
If Cayley had had the advantage of a really light power plant he would have been the first man to fly. But it did not come into existence in a form in which it could be made to fly in a man-carrying aeroplane until the Wright Brothers did it for themselves in the New World. Possibly the New World has a stronger mechanical sense than we have. This may be denied, but they really did get the engine which Cayley was looking for all the time. Perhaps if Cayley and Sir Hiram Maxim had been contemporaries we should have had flying in this country in 1885.

Another most significant point was Cayley's fundamental approach to flying. Many of the pioneers were interested only in flying for its own sake. They wanted to fly like the birds; that was their main object, they wanted to get into the air in controlled flight. Cayley wanted to use the atmosphere for transport; he wanted to fly to be able to get from point to point. That showed the great quality of the man; he did not want to fly for its own sake; he wanted to fly to improve civilisation. It was a tremendous thought.

Our lecturer himself is a historical figure. He is the architect of the modern Royal Aeronautical Society. The Chairman has told you that he became the Honorary Secretary in 1925; he did not tell you that the post was honorary because the Society could not afford to pay him. He went round England to get people to take interest, to support the Society by effort and money. He went round the country giving lectures and gave 100 in three years. He did all sorts of things to stimulate interest in the Society and gain it its place among manufacturers and those who were concerned with aeronautics.

During the 1939-45 War he saw the need to get the Society members together and organised meetings with the Operational Commands at which pilots, designers, service engineers and manufacturers talked over their troubles with complete frankness. With great foresight he recognised that we must have a society which went to the country and did not only stay in London. The Coventry Branch was formed in 1925. He recognised the need to make the Branches autonomous so that they could make their own local rules within a broad framework and could be founded on a small membership of the Society and all interested in aviation should come in and take part in the general deliberations. That, I think, was a very liberal, magnanimous and enlightened view.

He has done all these things and now he is writing the history of the Society and I do not think there is anyone else who could do it better. I am sure he will produce a tremendous result. He has a great historical sense and I think we are all privileged that he should come here this evening to tell us about this great Yorkshireman and deliver the first Cayley Lecture.



From a painting by Henry Perronet Briggs at Brompton Hall, near Scarborough.

SIR GEORGE CAYLEY

Was the First

1. To clarify the confusion of ideas about mechanical flight, and to lay down the principles of heavier-than-air flight.
2. To carry out experiments in aerodynamic research, for flying purposes, on the pressure on surfaces at various angles of incidence.
3. To use models for flying research.
4. To draw attention to the importance of streamlining and to outline the body of least resistance.
5. To show and discuss the movement of the centre of pressure of a surface in an air stream.
6. To discuss the problem of stability of an aeroplane, and to indicate methods to obtain stability.
7. To draw attention to the effects of the dihedral angle for wings, and of a movable tail plane and rudder.
8. To draw attention to the great importance of weight control.
9. To design a light aeroplane wheel.
10. To build a man-carrying glider.
11. To point out that curved surfaces had a better lift than plane surfaces, and that there existed a region of "vacuity" on the top surface.
12. To suggest the "internal explosion" (*i.e.* combustion) engine for aircraft.
13. To suggest jet reaction for propelling and steering air vessels.
14. To suggest the convertiplane, *i.e.* the combination of the fixed wing surface and vertical lift surfaces.
15. To suggest water recovery for airships.
16. To draw attention to the importance of the power/weight ratio, and of finding a light prime mover.
17. To invent the expansion air engine.
18. To invent the caterpillar tractor.

Sir George Cayley, Bart.

The Father of British Aeronautics

The Man and His Work

by

J. LAURENCE PRITCHARD, C.B.E., Hon.F.R.Ae.S., Hon.F.I.A.S., M.R.I.

"No little lily-handed Baronet he,
A great broad-shouldered genial Englishman."
ALFRED TENNYSON.

PART I—NON-AERONAUTICAL

THE TRUE BALANCE of a man's worth cannot be struck by a knowledge, however full, of only one of his activities.

I do not propose to confine myself to Cayley's aeronautical activities in this paper, for that would be to do much less than justice to a man whose interests, when known and understood, can only add to the stature of a great Yorkshireman and a great Englishman, one, to quote William Cobbett, "of the resident native gentry, attached to the soil, known to every farmer and labourer from their childhood, frequently mixing with them in those pursuits where all artificial distinctions are lost, practising hospitality without ceremony, from habit and not on calculation."

Sir Walter Raleigh, in his introduction to the *History of the War in the Air* (1914-1918), referred to Cayley as one who "amused his leisure with science." Raleigh was not aware and, indeed, very few who know something of Cayley's aeronautical work are aware, of how active was the interest Cayley took in scientific and engineering matters during his long life. I hope in this paper to add something to Cayley's stature, great as it is, in this respect.

Born in Scarborough on 27th December 1773, Sir George Cayley was a contemporary, in this country, of Thomas Young, of Young's Modulus and optical fame; of that great chemist John Dalton, author of the atomic theory; of Humphry Davy, the outstanding experimental physicist; and of James Watt and George Stephenson. On the Continent, Fourier, Poisson, Ampère, Arago and Carnot were laying down some of the foundations of science. He received tuition in mathematics and science. One of his tutors was the Rev. George Walker, F.R.S., President of the Literary and Philosophical Society of Manchester, and the other George C. Morgan, both exceptional men of their time.

These two men exercised a great influence on the young Cayley. The Rev. George Walker was a leading mathematician of his day and a Fellow of the Royal Society. He was an excellent mechanic, with a quick and inventive mind, and an eloquent speaker. George C. Morgan, a Unitarian Minister, had a high reputation as a writer on scientific subjects. He lectured on science and mechanics and his book "Lectures on Electricity" became well known. Both men played a lively part in the religious and political fields.

Their lasting influence was shown in many ways during Cayley's long life. He was a deeply religious man, a Unitarian, following in the beliefs of his mother, and for many years played a leading part as a Whig politician in local politics. Of his mechanical and scientific interests, which his tutors had inculcated in him, this lecture has much to tell. Such interests were part of his make up, for, like Toddy-one-boy-day he wanted to "see the wheels go wound." It has been written of him, by his daughter Catherine, "His early taste for mechanics showed itself by his spending every spare moment with the village watchmaker."

It must be remembered that at the beginning of the nineteenth century it was not easy for those interested in natural philosophy or science, to meet others interested, and many local societies were formed to enable the followers of science to find outlets for their activities. A number of these societies still deservedly flourish. Their proceedings are remarkable for the range and depth of many of the papers read before them. It was through membership of such societies that touch could be kept with contemporary discoveries and progress. The governments of that day were not very encouraging to science, and great scientific institutions were badly organised for making widely known what progress was being made.

Cayley had many scientific and engineering friends in this country and on the Continent. There is a considerable amount of correspondence available between them and Cayley, which reveal his range of thought and activity. J. E. Hodgson, who did so much to make known Cayley's pioneering work in aeronautics, records some 200 letters on aeronautical matters alone to Cayley between the years 1809 and 1850. Cayley was also a member of two important societies in Yorkshire, which he helped to found. One, the Yorkshire Philosophical

Society, founded at York in 1821, "to promote science in the district by establishing a scientific library, scientific lectures, and by providing scientific apparatus for original research," and the other the Scarborough Philosophical Society founded ten years later.

The Yorkshire Philosophical Society, of which Cayley was a Vice-President, was destined to play a leading, perhaps a vital, part in the spread of scientific knowledge. On 23rd February 1831, Sir David Brewster, well known as a scientist and discoverer of the polarisation of light, wrote to the secretary of the Yorkshire Philosophical Society, "I have taken the liberty of writing you on a subject of considerable importance. It is proposed to form a British Association of Men of Science. . . . My object in writing is to beg that you would ascertain if York will furnish the accommodations necessary. . . . if the Philosophical Society would enter zealously into the plan, and if the Mayor and influential persons in the town and in the vicinity would be likely to promote its objects."

Cayley was not only a Vice-President of the society but he was one of the influential persons in the town. The council of the society, the city of York, and its citizens responded zealously, and in the history of the British Association, published nearly a hundred years later, there appear the words, "The mother society of the British Association is the Yorkshire Philosophical Society, for it was in the name of the council of that body that the first public circular calling attention to the proposed meeting 'of the Friends of Science' was issued to other societies and to individual 'cultivators and promoters of science.'"

Cayley was a cultivator and promoter of science, as he had already abundantly shown. He is known nowadays as the Father of British Aeronautics, but as a Vice-President of the Yorkshire Philosophical Society, and a person of influence in York, he helped to mother the most remarkable of all bodies for the propagation of scientific ideas. Much of Cayley's influence in York came from the fact that he was Chairman of the powerful Whig Club of York. The President of the Yorkshire Society was Lord Milton who, largely due to Cayley's influence, had been elected to Parliament in 1807. Milton became the first President of the British Association, and at the same time his friend Cayley became a Life Member. Cayley remained also a Life Member of the Yorkshire and Scarborough Societies.

He was always ready to contribute towards the dissemination of scientific knowledge, as he was eager to learn. He not only helped to form societies, but he helped Baron de Ferussac to begin that encyclopaedia of knowledge, the *Bulletin Universelle* on the Continent. Three times Cayley tried to form an aeronautical society in Great Britain, the first time in 1816 when he wrote in *Tilloch's Philosophical Magazine*, "I wish to bring all those who interest themselves in this invention to act in concert towards its completion, rather than be jealous of each other respecting their own share of credit as inventors."

On 23rd January 1837 he sent to the *Mechanics' Magazine* a short paper on navigable balloons, following papers he had written in 1816 and 1817 in *Tilloch's Philosophical Magazine*. He ended his paper with the words:—

"Let the friends of aerial navigation be called together by advertisement in your pages, at the instigation of a few names favourable to the project; let a place —say the Adelaide Gallery, and some convenient day in next month be named, and from this meeting let such resolutions emanate, as may best ensure the progress of the Society for Promoting Aerial Navigation."

Three years later, at a meeting in the Polytechnic Institution, of which he was a Founder Member and Chairman, he appealed for the formation of a Royal Aerostatic Institution, "for extending the application and improving the practice of the art of Aerial Navigation." *See* Fig. 2.

J. E. Hodgson recalls that of the people Cayley approached, one, the Duke of Argyll* was an ardent supporter of heavier-than-air craft; another, Sir William Fairbairn, became one of the first members of Council of the Aeronautical Society in 1866; and two others, Robert Hollond and Charles Green, became early members.

This last appeal to form a society, like the others, brought an insufficient response, and in 1843 Cayley wrote in the *Mechanics' Magazine*, "I think it is a national disgrace . . . not to realise by public subscriptions the proper scientific experiments, necessarily too expensive for any private purse, which would secure to this country the glory of being the first to establish the dry navigation of the universal ocean of the terrestial atmosphere."

To go back a little, when in 1832 Sir George Cayley was elected to Parliament as the member for Scarborough, he took a house in London, and it was while there that he originated the idea of the Polytechnic Institution in Regent Street, for research work in and teaching of, engineering and science and for drawing the attention of the public to new discoveries in both subjects. In 1839 a Royal Charter was granted, in the name of Sir George Cayley and a Mr. Hampden, to the Institution.

A vivid light is thrown upon the struggle which went on in those days to obtain recognition for the importance of the objects of such an Institution, in a letter which Cayley wrote just before one of the meetings of the directors, of which he was the Chairman:—

"Mr. Nurse, the great builder, furnished the largest half of the capital and he and his friends (all for *money*, with science as the means) will have the main say at such a meeting. However we wanted more *science* and we wanted a sub-committee to carry on matter between the meetings of the directors. . . . We have laid out a good round sum of money, and the place by its laboratory, its theatre and its splendid gallery, is well adapted for the display of scientific discoveries, and were it truly in scientific hands, so that scientific discoveries were

*This was the seventh duke, father of the first President of the Aeronautical Society. He wrote to Cayley, on 6th June 1840, "I am as anxious as ever for the furtherance of the project, or I should rather call it the *Science* of Aerial Navigation." He made a special point in his letter of asking Cayley to visit him during the meeting of the British Association at Glasgow in September that year.

[1840]

PROSPECTUS

OF

A Society

FOR EXTENDING THE APPLICATION AND IMPROVING THE PRACTICE OF THE ART OF

AERIAL NAVIGATION,

TO BE ENTITLED

THE ROYAL AEROSTATIC INSTITUTION.

THE vast extent of the atmosphere, the paramount influence it exerts over all our movements whether of pleasure or of profit, the share which it contributes to the maintenance and formation of so many brilliant and important phenomena, and the ready means of transport it affords to bodies which are or might be fitted to avail themselves of its advantages, all combine to render it a subject of peculiar concern to the philosophical enquirer, and point with special interest to that Art, by means of which alone our acquaintance with it can be enlarged, or our dominion over it extended and confirmed.

Notwithstanding, however, the acknowledged interest and the magnitude of the results necessarily attendant upon success, it is remarkable how little has been hitherto attempted either with the design of improving the practice of Aerostation by the adaptation of new powers to the aerial machine, or of extending its application to such purposes as, even in its existing condition, it is peculiarly fitted to accomplish. Two or three ascents undertaken in the interests of science, and one solitary instance of the employment of the Balloon as an engine of military observation, are the only exceptions to the latter which present themselves throughout a period of nearly sixty years; while in respect of the former, notwithstanding the attention which it has occupied, and the ingenious speculations to which it has given rise, till within a few days past, not one serious experiment appears to have been tried or one feasible model executed for the purpose of illustrating the possibility of accomplishing the guidance of the balloon.

That it is to the great expense necessarily attendant upon all experiments in Aerostation upon the large scale, and not to any inherent obstacles to success, that this neglect is mainly to be ascribed, there is no doubt. The great size of the apparatus required for the support of only one individual, the costly nature of the materials employed in its construction, the expense incurred in the inflation, to be renewed every time it has to be used, with many others incidental to its maintenance and employment, all require a capital which few individuals have at their command, in that station of life, at least, to which the exercise of the art has hitherto been generally confined. It is only by combining together the resources of the many, that these objections can be removed; and with this view it is that the present Institution addresses itself to the notice and patronage of the public.

FIGURE 2. First page of the prospectus of an aeronautical society proposed by Cayley in 1840.

thrown off here hot from the brain and before they had become public property by publication, sufficient novelty would be produced to excite public attention and to make it pay. We much want a good scientific board confined by no aristocracy of orthodox men who sit like an incubus on all rising talent that is not *of their own shop*. . . . Freedom is the essence of improvement in science."

Those last eight words are worthy of being lettered in gold wherever scientific research is carried on.

In 1838 Cayley became an Associate of the Institution of Civil Engineers. He was a constant attendant at their meetings when he was in London, and frequently took part in the discussions or made in writing useful communications on the subject before the meeting.

Cayley succeeded to the family estates when he was only nineteen. They called for considerable attention and he made many agricultural improvements. He was one of the first to promote the drainage of land in Lincolnshire, where one of the family estates was situated. Much of it was under water, but by successful drainage methods he was able to grow wheat where formerly the land had only produced rushes and coarse grass. He was over a quarter of a century ahead of his neighbours in this respect. He was for over thirty years the chairman of the body responsible, under the Muston Drainage Act, for the effective drainage of many thousands of acres of frequently flooded land in the neighbourhood of his Yorkshire estates. At the time of the great floods in France in 1856 Cayley published the results of his experiences in the *Mechanics' Magazine* as a guide to methods of flood control which he had already shown had proved so successful.

Between the years 1800 and 1832 there was much distress in Britain. Cayley was on the side of reform and took a strong practical and personal interest in relieving hardship whenever he could. He was the first to initiate the allotment system, round about 1805, on his own estates. He did so on the grand scale, allowing every labourer capable of cultivating it, an acre of land. In the early forties when unemployment was rife in some of the mining and industrial districts of Yorkshire, he was one of the first to appeal publicly through the Press for contributions to a relief fund, as he was the first man to contribute in substantial measure, though he was nothing like as wealthy as many to whom he appealed.*

The example he set with his allotment schemes was widely followed for many years.

His concern for his own people was remarked upon by many, and an astonishing example of the practical outcome of that concern was the care he took over the son of one of his tenants, George Douseland, who had lost his hand. "I proposed to make him an artificial one," wrote Cayley, describing what he had done, "in the hope of rendering his loss rather less severe." The artificial hand, which he made in his own workshop at Brompton, attracted such attention that its wearer was presented at the annual soirée in 1845 of the Royal Society in London, to Prince Albert who, as the report stated, "sent specially for him in a separate room and shook him by his iron hand, and expressed himself much pleased with the ingenuity of its movements."

*His will at Somerset House showed him as leaving only £5,000.

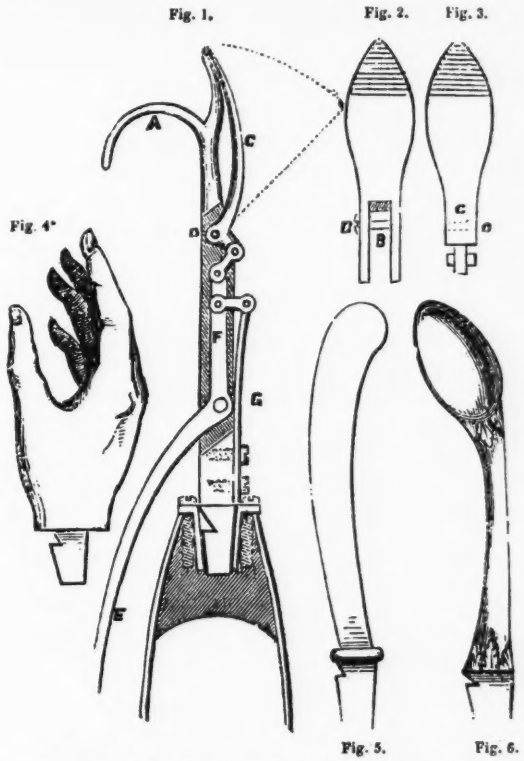


FIGURE 3. Mechanical limb designed by Cayley in 1845, with changeable fittings of a cork hand, knife and spoon and hook. Saws and other instruments could be fitted and used.

Later Cayley improved upon the mechanism (Fig. 3) so that the wearer was able to use a knife and spoon and, with special forceps, pick up small objects, as pins.

Cayley was not a mere dreamer of dreams. His ideas were based upon practical considerations, sound knowledge and, as far as he was able, upon the results of experiments. Cayley had the experimental outlook. In one of his last articles, which he wrote for the French Aeronautical Society in 1853, he appealed to the society to "occupy itself, under a scientific committee, with experimental results, rather than theoretical discussions." He knew his limitations and publicly acknowledged them, when he put forward suggestions for others to bring to their logical conclusions. "Nothing can more completely fall in with my views," he wrote in 1841 in an essay on Safety in Railway Carriages, "than to be enabled to show where, and by whom, the improvement contemplated can best be obtained."

In the *Mechanics' Magazine* for January 1826 appeared the astonishing drawing shown in Fig. 4, headed, "Sir George Cayley's Patent Universal Railway." It was Patent No. 5260 of the previous year.

"This invention which may be called the universal railway, is for the purpose of forming locomotive vehicles by which the impediments and resistances of every sort of road, land, morass or water will be

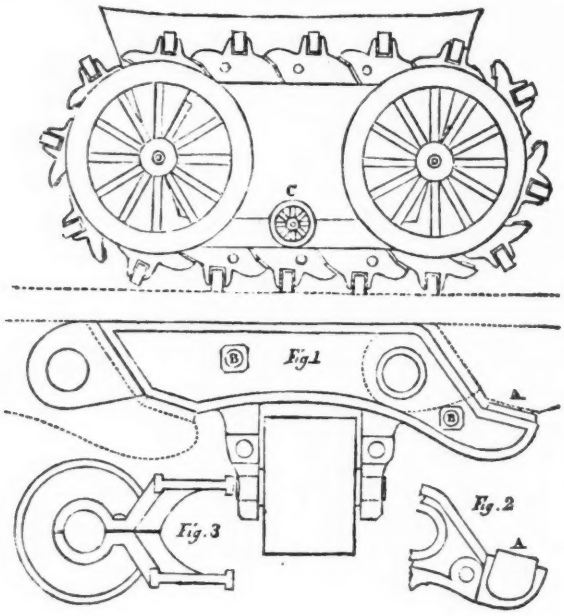
Mechanics' Magazine,

MUSEUM, REGISTER, JOURNAL, AND GAZETTE.

No. 127.] SATURDAY, JANUARY 28, 1826. [Price 3d.

"That pains we take in books or arts which treat of things remote from the use of life, is but a busy idleness."—*Fuller.*

SIR GEORGE CAYLEY'S PATENT UNIVERSAL RAILWAY.



VOL. V. Q

FIGURE 4. Facsimile of the first page of the *Mechanics Magazine* for January 28 1826, showing the forerunner of the caterpillar tractor, Patent No. 5260 of 1825.

obviated or overcome," wrote Cayley. "This is effected by placing in succession under the wheels of vehicles such sort of supporting structures of any dimensions, bearing a rail or train as may suit the species of way the vehicle is calculated to pass over."

These words are taken from Cayley's manuscript notes and are followed by a detailed description of what is now known as the caterpillar tractor. Fig. 5 shows a page taken from Cayley's notes.

"In the case of the vehicle being applied to water," added Cayley, "a much greater magnitude of parts will be necessary—each link may then consist of extended framework with diagonal braces tho' applied in the same manner as to its mechanical operation, and a boat or other shaped water-tight float will form the supports under each link."

Cayley always showed a great interest in engines and powered vehicles and employed a trained mechanic named Vick to build the engines at Brompton Hall. He foresaw clearly the great developments which were coming, and tried to develop an engine "for affording mechanical power from air expanded by heat," to quote the heading of a letter he wrote in 1807 to *Nicholson's Philosophical Journal*, with a view to producing an engine in place of the steam engine, "which has hitherto proved too weighty and cumbersome for most purposes of locomotion."

In Cayley's Aeronautical and Miscellaneous Notebook, found some years ago by the late Honorary Librarian to the Society, J. E. Hodgson, Cayley wrote, under the date 22nd November 1807, "Being in want of a simple and light first mover on a small scale for the purpose of some preparatory experiments on aerial navigation, I constructed one in which the force of gunpowder and the heat evolved by its explosion acting upon a quantity of common air, was employed."

The gunpowder engine (Fig. 6) was simple and easy to make. A piston was driven upwards by the force of the explosion of a given amount of powder and brought back after the explosion by means of a bow or spring. Cayley calculated the horsepower he obtained but gave no particulars of the weight of his model engine. He abandoned it in favour of the hot air expansion engine with which he experimented for the next forty years, as did many others.

At a lecture by James Stirling in 1845 before the Institution of Civil Engineers on the hot air engine, Cayley admitted he had not succeeded in getting as low a consumption of fuel per horsepower as that obtained by the lecturer. The use of heated air as a motive power was the subject of another lecture before the Institution in 1853, when reference was made to the fact that "the first approach to a practical caloric engine was that invented by Sir George Cayley. For many years," added the speaker, "Cayley's attention was almost exclusively devoted to the subject, and eventually, in 1837, one of these machines was reported by Goldsworthy Gurney and G. Rennie to be doing a duty equal to 5 h.p. with expenditure of 20-22 lb. of coke per hour."

Stirling, in his lecture, declared, "such an engine moved all the machinery at the Dundee Foundry Cos. works for 8 to 10 months and was capable of raising 700,000 lb. one foot per minute, and a bigger one, lifting 1,500,000 lb. one foot per minute was being built."

Cayley himself contributed a long written contribution, which showed that he still had a lively interest, at the age of 80, in his early love, and in the improvements which had been made in its construction.

Sir Goldsworthy Gurney, the eminent scientist and engineer, and long a friend and associate of Cayley, declared in the discussion that, in his opinion, Cayley's air engine was superior to those being developed, in that Cayley heated the air directly in contact with the fuel to obtain power. Gurney was not a man to praise easily. At one time great hopes were held out for this type of engine and at the time of the lecture Ericsson, in America, had fitted a ship, appropriately named the *Caloric*, with one.

Cayley's first published paper in *Nicholson's Journal* was a description of an engine for affording mechanical power from air expanded by heat. Although it is

extremely wasteful in large engines, owing to the fundamental difficulty of heating a large volume of air, pumping engines on this principle are still in use.

Cayley constantly had in mind the necessity of a light engine if successful flight were to be achieved. He suggested the use of hydrogen or carburetted hydrogen gas as a fuel, as offering a lower weight per horsepower than existing engines. Although the hot air engine was to prove a failure from a flying point of view, in discussing it he said, "a much cheaper engine of this sort might be produced by a gas tight apparatus and by firing the inflammable air generated with a due proportion of common air under a piston." He suggested the use of oil of tar for the explosive fuel, and but for the accident of concentrating first on the expansive power of hot air, he might have laid down some of the foundations for the internal combustion engine.

It was not unnatural that the coming of the railway should interest a man of Cayley's calibre. The newspapers in the second quarter of the nineteenth century were full of advertisements for railway construction, appeals for money, and of accidents on existing stretches of line. These accidents disturbed many. Sir George Cayley was present when Huskisson was killed at the opening of the important Manchester and Liverpool Railway in 1830. Between 1830 and 1845 he suggested a number of safety measures in various papers in the *Mechanics' Magazine*.

The average speed of trains in those days was of the order of 21 m.p.h., including stops. Cayley's first suggestion was for a special buffer to be fixed in front and behind every train in addition to the normal carriage steel-spring buffers, which he calculated were not strong enough to do more than minimise disaster at the speeds then prevailing. Cayley made the suggestion to use the power of compressed air, "luckily the elasticity of air when compressed by a piston offers a ready means for effecting this purpose."

First class carriages were fitted with padded cushions to lessen shocks, and Cayley sharply stated that they should be fitted in all carriages, for, said he, "each man's life is equally valuable to himself, and should be equally protected." In view of the present day air transport safety precautions, it is of interest to note that Cayley drew attention to the proposed use of a broad padded belt to retain each passenger in place in case of accident, although he declared he did not fancy John Bull being in a strait jacket! Times have changed since his day!

Cayley also suggested, with practical diagrams for construction, how the compression of the carriage buffers could be used so as to apply the brakes automatically.

He was very conscious that he must appeal for these safety reforms in a way which would be understood by the ordinary reader and stir his imagination by drawing homely analogies of the effects of the sudden stoppage of a train by collision. He pointed out that though the average speed was 21 m.p.h., "double the speed is frequently attained in descending inclined portions of the way. In this case the blow would be equal to that received in falling down from a height of about sixty-four feet. This is falling from the chimney top to the cellar—an experiment not to be tried twice in one man's lifetime."

Cayley was very strongly of the opinion that the human factor, as one of the causes of railway accidents,

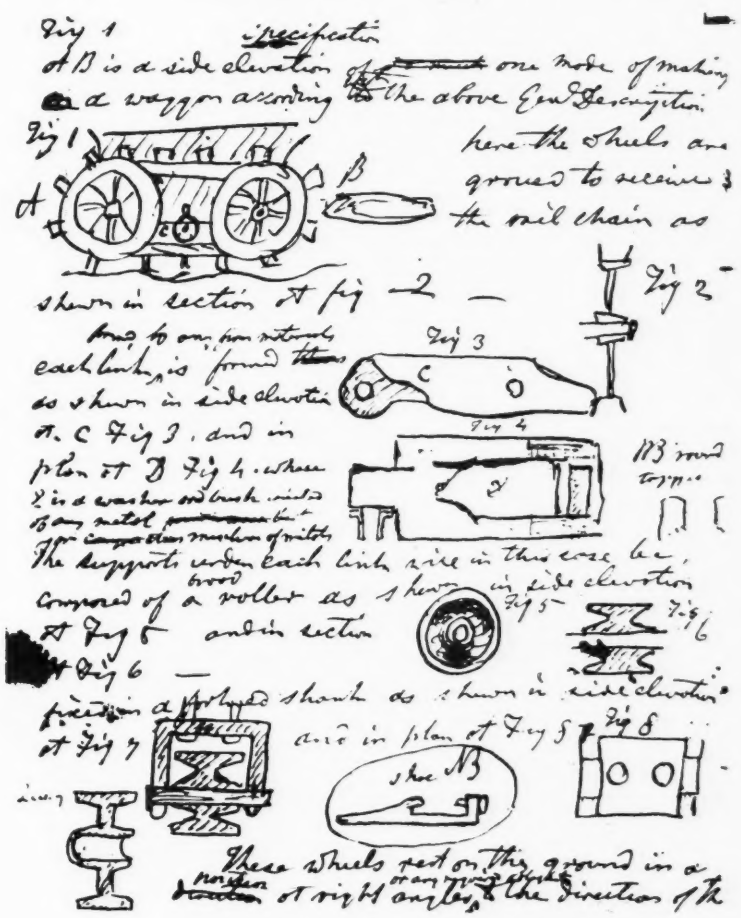


FIGURE 5. Page from Cayley's notes showing his rough sketches for his caterpillar tractor.

should be eliminated as far as possible. With this in mind he drafted out an automatic block system of control on the railways. "Suppose that signal posts be placed at a mile distance from each other on each side of the railroad. . . . By a contrivance detailed later, every train that comes up to one of these posts causes its red signal to be hoisted, which continues up till the train proceeds a mile further, and has arrived at the next post, in passing which the signal on the first post is withdrawn. . . . In the case of fogs a bell should likewise be so arranged as to ring on the train passing any post showing the red signal."

In his paper, Sir George Cayley enters closely into the details, with constructional diagrams, for the working of such a system, even, ingeniously, making allowance for the expansion and contraction of a mile length of controlling wires covering each section, so that the wire is always at the same tension. He further suggested that there should be automatic signals in the driver's cabin which would indicate how points were set, so that, "he may become fully aware how they are placed before he comes up to them."

It is a little difficult in these days to realise what speeds of 20 to 40 m.p.h. meant to the general public. "There is quite terror enough in the public mind on the subject of railways," wrote Cayley, "and it is therefore well to make calm estimates of the degree of danger attending such cases of possible occurrence as this." In a further note in 1845 he declared, "as crows only fly at twenty-four miles an hour, men, not born with wings, ought to be contented to rival in speed those so gifted by nature, and that if they will not be so contented they should not grumble at the consequences."

Perhaps the situation as far as the public was concerned can be realised when Cayley wrote, "It is necessary to make it a positive law, that the up trains shall always keep to one set of rails, and the down trains to the other."

It may be thought that I have already paid too much attention to those activities of Cayley which do not ordinarily concern aeronautical technicians, but what I have said only sketches in some of the high lights of this very remarkable man. He read widely and was noted for his encyclopaedic knowledge, and had a broader and more balanced outlook upon human affairs than can be obtained by most in the ever-increasing specialisation of the modern world. The humanities to Cayley were real.

In the Memoir of Cayley printed in the Proceedings of the Institution of Civil Engineers it is stated that in later years he directed his attention to optics and made some useful discoveries, "which were followed by the construction of an instrument for testing the purity of water by the abstraction of light; a process which has lately been used with success in the investigation of the waters of the Thames. He also attempted the application of electricity as a motive power." Further, Cayley was interested in a new type of self-righting lifeboat, in Absolute Zero, the permanent defence of the country against attack from the Continent, architecture, acoustics of buildings, and the study of natural flight. He had fixed on his bed a telescope and he used to knock up his manservant early in the morning to see celestial phenomena.

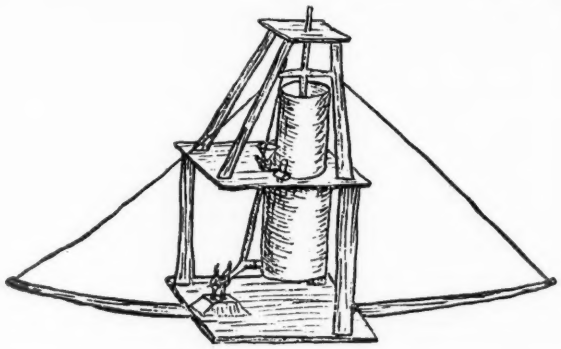


FIGURE 6. Cayley's experimental gunpowder explosion engine "a simple and light first mover."

In June 1846 there was published an account of experiments which had been made with "rifle shots weighing an ounce and three-quarters, of the form of a sugar loaf," by the Government. Cayley immediately wrote to the *Mechanics' Magazine*, "Having tried many experiments on six-pound cannon shots of various forms, about the years 1804-05, for which the late Lord Mulgrave allowed me powder from the government depot at Scarborough, and the use of a six-pounder gun, I send you a description of the shots then used. My object at the time was to ascertain whether, by obviating as much as possible the resistance of the air, the range of cannon shot might be increased."

In the second half of this paper it will be found that Cayley paid much attention to finding the right kind of shape to lessen the resistance, or drag of aeroplanes and airships, so these experiments were not without their significance. One of the shells he tried was almost the replica of the bomb shapes used in the early days of the 1939-45 War, with guiding fins.

Cayley lived in the days of the giants of the dawn of science and may be misjudged accordingly. But for those who so easily, in the middle of the twentieth century, excel Newton and Faraday and Watts in their knowledge before their twentieth year, one may recall that in 1828, while on a visit to Paris, Cayley was struck by the controversy about Absolute Zero. In those days heat, or caloric as it was called, was conceived as a kind of all-pervading, imponderable, highly elastic fluid the particles of which were attracted by matter and repelled by one another, a conception which dominated the science of heat until the work of Joule and Mayer in the middle of the century, despite the fundamental experiments of Rumford and Davy.

In a note in the *Philosophical Magazine*, "On the Natural Zero in the Fahrenheit Scale," Cayley wrote, "I send you the following considerations respecting the natural zero, which though not perfectly conclusive, yet lead to a strong probability that the point of absolute privation of transferable caloric, takes place at 448 degrees of Fahrenheit's scale below his 0°."

He based his arguments on Rumford's work, and he was obviously aware of the experiments which were

being made on the mystery of heat. Indeed, he did not put forward any conclusions, experimental or theoretical, without a knowledge of what others were thinking and doing, in this way differing from so many of whom it may be said: "He is a dreamer; let us leave him."

In 1808 the famous Covent Garden Theatre, which afterwards became the Royal Opera House, was burnt to the ground, and in *Nicholson's Journal* a few months later there appeared a long letter, illustrated with diagrams, from Cayley, outlining proposals for various improvements which he thought should be made in the construction of theatres. He was interested in acoustics and he suggested the plan form of a theatre should be in the form of an ellipse, with the stage enclosing one focus, and with a curved roof, so that speech and sounds from the stage would be reflected to all parts of the house. Forty-eight years later, when the Opera House was again burnt down, the *Mechanics' Magazine* reprinted Cayley's letter and illustrations with the footnote, "The above letter, though written nearly fifty years ago, is so applicable to the present time that . . . we have extracted it from *Nicholson's Journal* in 1809, with the hope that it will receive the attention of the architects of the new theatre about to be erected."

Sir George Cayley was "A proper man, as one shall see in a summer's day," who believed with Samuel Johnson that "example is always more efficacious than precept," and was deeply interested in world affairs.

PART II—AERONAUTICAL

"I do not know what I may appear to the world, but to myself I seem to have been only a boy playing on the sea-shore and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."
ISAAC NEWTON.

In an unfinished, unpublished essay, dated 6th October 1804, on the Mechanical Principles of Aerial Navigation, Cayley began with the words, "The materials from which the present essay is derived have been several years in my possession in the form of unconnected considerations relative to the various parts of the subject being merely written in the order in which the ideas suggested themselves."

He continued, later in the essay, "I have kept the subject to myself for 8 or 9 years during which I have made many experiments preparatory to the main object but I find that the progress of an individual occupied by other matters is very slow."

In this essay he gives his opinion that man will never be able to fly under his own power, as birds do, a will-o'-the-wisp hope which is still followed by a few aeronautical technicians. Cayley was more practical in his belief, and was of the opinion that a 2 h.p. engine weighing less than the average man could be constructed, and so simplify the solution to the problem*.

There the brief essay ended, and it was not until five years later that Cayley was able to finish it and there was published in *Nicholson's Journal* that astonishing paper on Aerial Navigation which was so far in advance of anything written or done before, in theory or in experiment.

The essay of 1809 was critically assessed by Orville Wright a little more than 100 years later. On 9th December 1912 he wrote to Henry Woodhouse, "Sir George Cayley was a remarkable man. He knew more of the principles of aeronautics than any of his predecessors, and as much as any that followed him up to the end of the nineteenth century. His published work is remarkably free from error and was a most important contribution to the science."

Alphonse Berget, President of the Société Francaise de Navigation Aerienne, wrote in 1909, on the centenary of the publication of Cayley's paper, "He was the incontestable forerunner of aviation, whose name should be inscribed in letters of gold, on the first page of the aeroplane's history."

On 26th December 1904 Octave Chanute wrote to Wilbur Wright, "I have now a curiosity to know what are your final conclusions as to the power actually required for artificial flight, and whether you hope to reduce it. I am under the impression that birds use less power than you have found necessary."

I consider that Wilbur Wright's reply to Chanute paid just as high a tribute to Cayley as his brother Orville paid nearly eight years later. It indicated to what extent the brothers had paid attention to what Cayley wrote.

"Your suggestion regarding the power expended by birds found us considering that very point, having been led to consider the subject by the very ingenious calculations of Sir George Cayley. He attempts to compute the power expended by a crow in its flight but the result obtained was too favourable in his opinion, and I am inclined to think the same, though I have been unable to complete some calculations of a somewhat similar nature from a lack of definite information regarding the tip to tip measurement of a crow."

Chanute replied, "Cayley mentions the rook and the crow indiscriminately, and he estimates it to weigh one pound per square foot of surface, which probably obtains after the bird has had breakfast!"

Chanute himself, in his classic work *Progress in Flying Machines* refers to the way in which Cayley ingeniously "evades the then prevailing confusion." Cayley began with the weight of the bird, which could be easily ascertained, instead of the area of the wing and

*Those were the days when the weight per horsepower of a steam engine was of the order of 150 to 250 lb. according to the job it had to do. Fifty to sixty pounds per h.p. would appear incredibly low to Cayley's contemporaries.

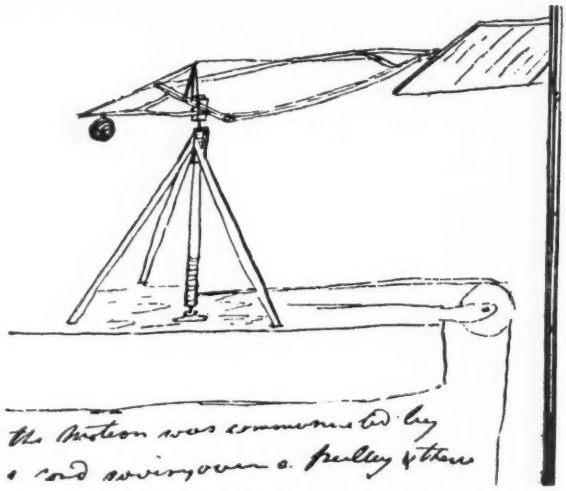


FIGURE 7. Cayley's sketch of his whirling arm apparatus.

its speed, so that in the beginning he was not confused by having to consider what the pressure was on a plane at a given angle of attack and a given speed. Wilbur Wright in his very first letter to the Smithsonian Institution on 30th May 1899 wrote that he had been interested in the problem of mechanical flight ever since he had constructed a number of models of various sizes "after the style of Cayley's and Penaud's machines."

In the discussions following the lectures read before the Society in the nineteenth century, Cayley was often quoted as the authority. That great Frenchman, Alphonse Penaud, in his paper in *L'Aeronaute* in 1876, stated that he had carried out certain experimental measurements of bird flight to ascertain the angle of incidence and so the loading on the wings, and pays a tribute to Cayley for the accuracy of the results Cayley had obtained seventy years before.

Magoun and Hodgins, of the Massachusetts Institute of Technology, in their *History of Aircraft* wrote, in 1931, before Cayley's Notebook was discovered:

"His experiments both with lighter and heavier than aircraft make his name not only national but international. His was the first front-rank intellect to undertake the study of aerodynamics since General Meusnier had studied it more than a quarter of a century before. Between these two, the parade of mediocrity in scientific experimentation had stood in unhappy contrast to the fervor and daring of practical men engaged in using aircraft for voyages and for exploration. Cayley remains to this day unique in the catholicity of his views . . . Cayley was the first man definitely to suggest the necessity for streamlining . . ."

The authors head part of their work "The Pre-Cayley Era'" and added:

"Unless the student of aeronautics wishes to assume the crochet of believing in the wooden pigeon of Archytas, or the iron fly of Johann Muller, he must doff his cap once again to Sir George Cayley as the father of the successful navigation of the atmosphere by means of heavier than air. It was he from whose amazing mind there sprang the definite suggestion of a rigid-plane mechanism driven through the air by propellers connected to an efficient source of mechanical power."

And, today, one hundred and fifty years after Cayley began his essay on Aerial Navigation, von Kármán, in his book *Aerodynamics* (published in 1954), wrote, "The idea that sustentation can be accomplished by moving inclined surfaces in the flight direction, provided we have mechanical power to compensate for the air resistance, was probably clearly defined for the first time by an Englishman, Sir George Cayley, in his paper published in 1809-10 on aerial navigation . . . in his paper he clearly defined and separated the problem of sustentation, or in modern scientific language the problem of lift from the problem of drag."

It is unfortunate that in the two reprints of Cayley's first paper by the Society in 1876 and 1910, a number of paragraphs were left out by the editors. The paper is reprinted in full in the Appendix to this lecture, with a note of the edited passages. In one of the struck out paragraphs Cayley wrote, to the editor of *Nicholson's Journal*, "I am induced to request your publication of this essay, because I conceive in stating the fundamental principles of this art, together with a considerable number of facts and practical observations that have arisen in the course of much attention to this subject, I may be expediting the attainment of an object that will in time be found of great importance to mankind; so much so, that a new era in society will commence from the moment that aerial navigation is familiarly realised."

The first statement of principle made by Cayley concerned the power required. "Lightness is of so much value," he declared, after rejecting the steam engine as being too heavy for his ideas, "that it is proper to notice the probability that exists of using the expansion of air, by the sudden combustion of inflammable powders or fluids, with great advantage. . . . Probably a much cheaper engine of this sort might be produced by a gas-tight apparatus and by firing the inflammable air with a due portion of common air under a piston."

Cayley drew attention to the importance of a low power weight ratio for increasing payload, "in such proportion may aerial vehicles be loaded with inactive matter."

It was after a brief, but so significant discussion on the forces on a bird in gliding flight (*see* Fig. 1 Plate 1 of the Appendix) that Cayley made the statement, "The whole problem is confined within these limits—To make a surface support a given weight by the application of power to the resistance of air," and added, "Magnitude is the first question respecting this surface." By this he meant a knowledge of the magnitude of the forces on a surface moving at a given speed and angle of incidence through the air, as that was the first and necessary knowledge required towards finding the solution of the problem of flight.

He quoted Smeaton's result that a surface of a square foot met with a resistance of one pound at a velocity of 21 ft. per second and said that he had made many experiments upon a large scale to check that figure.

In his Notebook he records that these experiments were made in 1804 with a home-made whirling arm. He describes at some length the care he took to obtain as accurate measurements as he could. Fig. 7 shows a sketch of his apparatus taken from the Notebook. A surface of one foot square was carried round on an arm which could move up and down in a vertical direction. The pressure was measured at angles of 3°, 6°, 9°, 12°, 15° and 18°. Here is a copy of the table of results at a speed of 21·8 feet per second, taken from his notes. The whirling arm was balanced by a weight against the lift.

Angle	*Weight supported* (*oz.*)
3°	1·0
6°	1·5
9°	2·5
12°	2·75
15°	4·125
18°	5·187

In a further set of readings at the same angles, but at a speed of 15 ft. per second, corresponding results were obtained.

Although a similar apparatus had been used before Cayley to measure the pressure of the wind, these experiments were the first to measure air pressures at various angles of incidence and air speeds to obtain aerodynamic data for flying purposes.

"The experiments were done with great care," Cayley wrote, "and often repeated with the same results, and made on such a large apparatus and upon so long an average that they must be tolerably correct. I had not a barometer to note the weight of the atmosphere at the time."

One is well aware of the roughness of Cayley's apparatus and the errors involved in measurements, but that does not detract in any way from the high importance of this pioneer aerodynamic research. Cayley himself was fully aware of the difficulties in obtaining exact results and he made allowance for errors. It is of interest to note that many aerodynamic measurements of the present day still follow Cayley's example of 3° intervals.

One of Cayley's reasons for these experiments was to test that an air speed of 21 ft. per second gave a pressure of one pound on the surface of one square foot at right angles to the air stream. His whirling arm mechanism was not powerful enough to enable a pressure much greater than half a pound to the square foot to be measured. That pressure he obtained at a speed of 17·16 ft. per second. He assumed that the pressure varied as the square of the speed over the surface, and he calculated the speed for a pressure of one pound to be 24·287 ft. per second, as against the 21 ft. per second of Smeaton. A second experiment gave him a figure of 23·1 ft. per second and Cayley wrote in his essay, "I shall therefore take 23·6 ft. per second as somewhat approaching the truth."

For safety's sake he erred on the right side of truth.

"I have my doubts, however," he added, "whether this mode of circular motion does recreate as much resistance as when the plane moves on a right line keeping parallel to itself." (It must always be remembered that Cayley used the word resistance for either lift or drag. Usually the context makes it clear in which sense it is used.)

To test his opinion he made a model aeroplane.

"A common paper kite containing 154 sq. inches was fastened to a rod of wood," he explains (*see* Fig. 8 for Cayley's rough sketch taken from his notebook), "and supported from the forepart from the same rod by a peg, so as to make an angle of 6°. With it this rod proceeded on behind the kite and supported a tail made of two planes crossing each other at right angles, containing 20 sq. inches each. This tail could be set at any angle with the stick."

Not only was the tail plane adjustable but the centre of gravity of the model could be varied by a movable weight.

"It was very pretty to see it sail down a steep hill, and it gave the idea that a larger instrument," wrote Cayley, "would be a better and safer conveyance down the Alps than even the sure-footed mule, let him meditate his track ever so intensely. . . . The least inclination of the tail towards the right or left made it shape its course like a ship by the rudder."

These were the first experiments ever made with a model aeroplane, having adjustable means of control, in order to test experimental figures obtained in another way. As a result of them Cayley found that at 15 ft. per second his model supported 2·85 oz. to the square foot, "and therefore," he added, "at a velocity of 21 ft. per second it would support 5·6 oz., whereas by the tables of circular velocities there appeared only a support of 1·5 oz. Crows have a foot surface and move 34·5 ft. per second supporting a pound, and the angle is not perhaps more than 3° or 4°. However their wing is

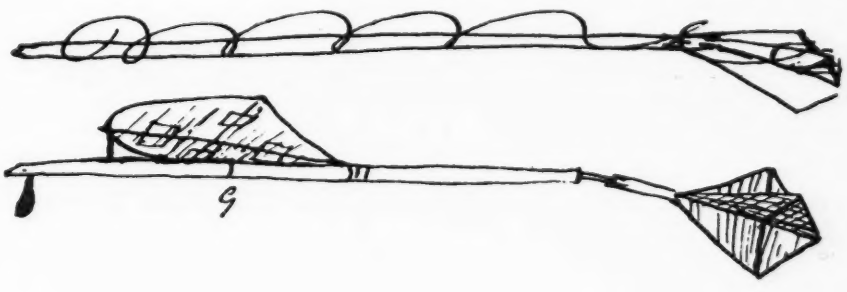


FIGURE 8. Sketch from Cayley's Notebook of a model experimental aeroplane with adjustable tail and rudder and movable centre of gravity. This was the first experimental aeroplane model ever made.

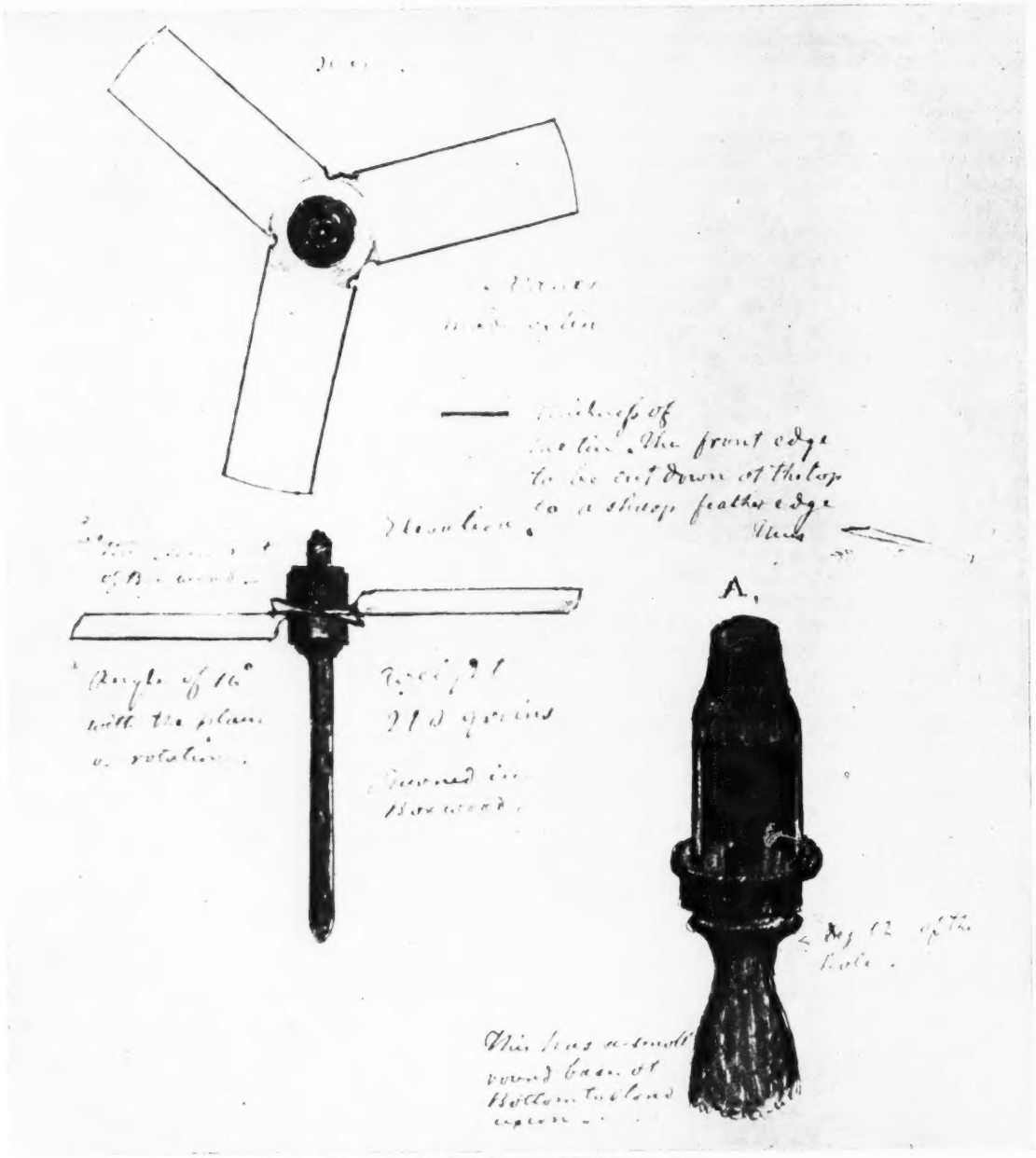


FIGURE 9. Cayley's improved Chinese top toy.

concave, which resists much more than a plane surface, and the paper on the kite may not be tight."

Cayley wrote that his model glided at an angle of 18°, so that the weight supported per sq. ft. was far less than his statement. It is curious, with all his normal caution over measurements, that he made no comment on this point. He appeared unaware of the many parameters involved. All his calculations were based upon the unit of one pound of lift for one square foot of surface. He did not make any statement about the position of that square foot on the aeroplane wing, or the nature of the edges, the smoothness of surface and its linear dimensions.

It is known that Cayley's first ideas about mechanical flight came in the year 1792, when he was only 18 years of age. He made a helicopter toy of feathers, corks, a shaft of wood, string and a whalebone bow for power (*see* Plate 1 Fig. 3 of the Appendix).

As regards this toy and helicopters on a large scale, Cayley comments, "for the mere purpose of ascent this is perhaps the best apparatus; but speed is the great object of this invention (*i.e.* the aeroplane) and this requires a different structure." In later years he developed a variation of this toy, the Chinese top shown in Fig. 9, and he spoke of it as "a very beautiful specimen of the action of the screw propeller in the air."

Immediately following the description of a helicopter toy, Cayley discusses the problem of lateral and longitudinal stability of a fixed wing machine, and notes that the position of the centre of gravity and the centre of pressure do not usually coincide. He stated, "aided by a remarkable circumstance that experiment alone could point out," at very acute angles of incidence the centre of pressure moves considerably in front of the centre of gravity of a wing.

Wenham, in his own classic paper of 1866, commented, "From this discovery, it seems remarkable that Sir George Cayley, finding that at high speeds with very oblique incidences the supporting effect became transferred to the front edge, the idea should not have occurred to him that a narrow plane, with its long edge in the direction of motion, would have been equally effective."

Herbert Chatley in his paper on the Centre of Pressure on Aeroplanes, in *Aeronautics* for 1909, drew attention to the fact that Cayley was the first man to point out the non-coincidence of the centre of gravity and the centre of pressure of a wing at small angles of incidence, and that "Subsequent practical determinations have been made by Hagan, Joessel, Kummer, Langley, Phillips, Turnbull and Lanchester."

As regards Wenham's comment, Cayley may have been aware of aspect ratio, although he did not express it in clear terms. In his Notebook, under the date 19th February 1808, he states that he had shot a heron. After giving its measurements, area of wings, and weight, he notes, "This bird seems peculiarly light upon wing and wafts very slowly. Its wings are very concave and are not in one plane, but in an arch. . . . I observe this arch likewise in the sea-gull, which is also a light bird. I am apt to think that the more concave the wing to a certain extent the more it gives support and that for slow flights a long thin wing is necessary, whereas for short quick flights a short broad wing is better adapted, with a constant flutter as the partridge and pheasant. But the convenience of the circumstances of the bird regulates the kind of wing that can be commodiously given them."

In a later paper Cayley drew attention to the fact that with large aircraft a long narrow wing might be difficult to construct with the necessary margin of strength with the materials then known, and that biplanes and triplanes would give better structural solutions. Cayley does not state specifically that he was aware of the importance of aspect ratio, but, nevertheless, he was clearly aware of the differing ratio required for differing flying conditions.

Following a description of the type of construction required, especially from the point of view of stability, to which he attached great importance, Cayley in his paper describes a glider of 300 sq. ft. which he made (*see* Appendix) and gives a note of its weight. Short glides were made and Cayley had the intention of fitting a motor, but the machine was accidentally broken, although "its steerage and steadiness were perfectly proved, and it would sail obliquely downwards in any direction according to the set of the rudder."

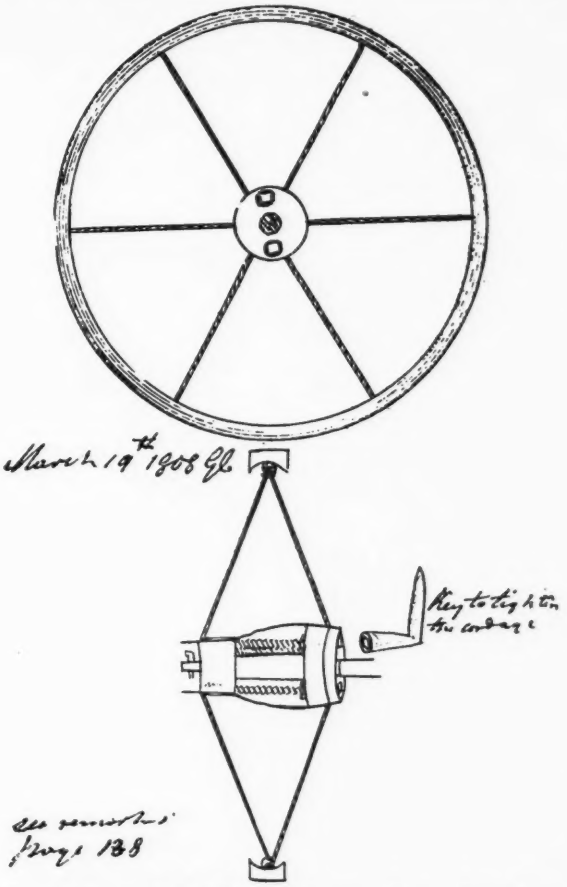


FIGURE 10. Cayley's light wheel for aeroplane undercarriages, the forerunner of the bicycle wheel.

It is of interest to note that the final experimental glider of the Wright Brothers at Kitty Hawk was 305 sq. ft. in area, greater than any area tried by Chanute, Lilienthal or Pilcher, the last two of whom lost their lives, so it would have been astonishing if Cayley had succeeded in preventing disaster should he have attempted any serious gliding with such a frail structure and inadequate controls. Nevertheless these experimental beginnings were most remarkable. Those were the days when men had more leisure to philosophise on the difficulties of a problem and still keep their faith in ultimate success.

"Many mechanical difficulties present themselves," he wrote in *Nicholson's Journal*, "which require a considerable course of skilfully-applied experiments before they can be overcome . . . but no one can doubt the ultimate accomplishment of this object."

Cayley put forward a number of suggestions for the construction of possible aircraft in order to avoid, to use his own words, "the general difficulties of structure in aerial vehicles (arising from the extension, lightness, and strength required in them, together with great firmness in the working parts, and at the same time such an arrangement as exposes no unnecessary obstacles to the current) . . ."

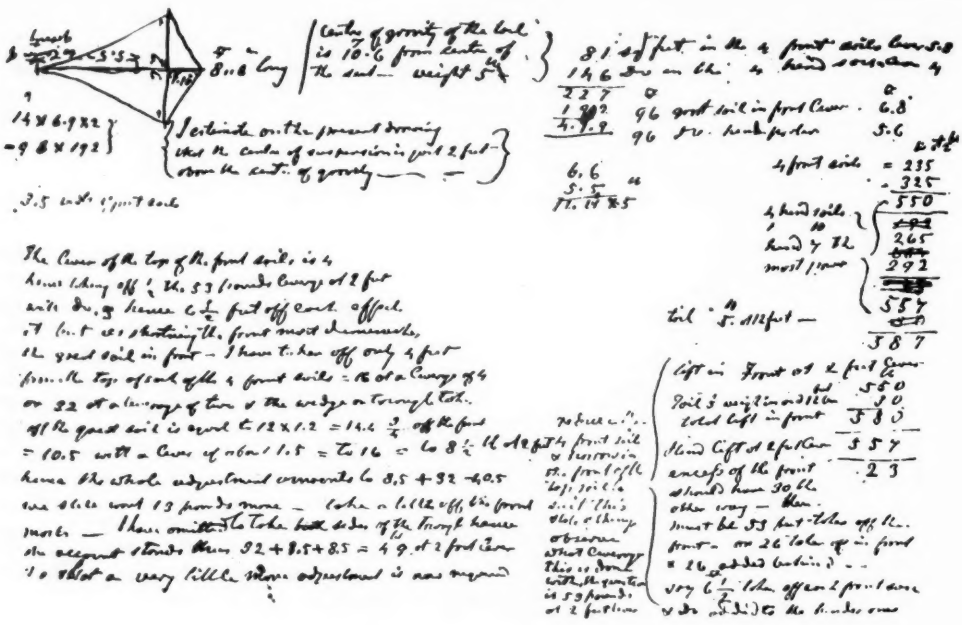


FIGURE 11. Cayley's notes on his experimental kite of 1808.

It will be noted that his words in brackets outline the difficulties which remain to this present day, lightness, with the necessary strength, and streamlining to give the minimum resistance.

It is convenient here to give some particulars of Cayley's undercarriage wheel, for no account, however brief, and inadequate, of Cayley's experiments can leave out a reference to it. Fig. 10 shows an illustration of the tension or suspension wheel from Cayley's Notebook, dated 19th March 1808. There he wrote, "In thinking how to construct the lightest possible wheel for aerial navigation cars, an entirely new mode of manufacturing this most useful part of all locomotive machines occurred to me—*vide*, to do away with wooden spokes altogether and refer the whole firmness of the wheel to the strength of the rim only, by the intervention of tight strong cording. Such a wheel would, I am confident, be almost everlasting for light travelling vehicles." He added, in his paper of 1853, that during flight they were a superfluous incumbrance and that was a cogent reason why they should be of the lightest possible structure.

Cayley gives a lengthy description for its construction and for a method of tightening the cords when necessary. This was before the era of the bicycle and he overlooked that it was necessary to insert the cords tangentially in the hub to transmit the power.

It was about this time that he made a series of calculations for his experimental kite. (*See* Fig. 11).

In 1826, when T. Jones took out his patent for a suspension wheel, Cayley believed his secret must have crept out, but Jones had developed the idea quite independently, and had quickly patented it. The light engine, light construction, light undercarriage, all indicated how much importance Cayley attached to lightness as one of the factors in successful flying.

The fundamental difficulty which Cayley faced was how to make use of the power of an engine for forward flight. He believed that some part of the wings must move, but was certain that with large machines flight could be obtained "by using the continued action of oblique horizontal flyers," that is, by a form of airscrew, and that no more moving surface would be used for the propelling power, "than is barely necessary."

He constructed a specimen pair of wings with a surface of 54 sq. ft., for a weight of 11 lb., which lifted 9 stone, and states that by careful construction with existing materials, surfaces could be made "with a greater degree of strength and lightness than any made use of in the wings of birds." Cayley emphasised that these flapping wings "were constructed for the purpose of an experiment relative to the propelling power only," for he was sure that, except for any moving surface necessary for propelling an aeroplane forward, the main surfaces would be fixed.

On the question of drag he reiterated the importance of lessening it in every way possible. "Let it be remembered," he said, "that every lb. of direct resistance that is done away with will support 30 lb. of additional weight without any additional power*," and added, caustically, for those who believed in manpower flight, "The figure of a man seems but ill-calculated to pass with ease through the air, yet I hope to prove to the full as well-made, in this respect, as the crow."

I commend Cayley's final words on streamlining, "I fear that the whole of this subject is of so dark a nature as to be more usefully investigated by experiment than by reasoning."

It still appears that way, I fancy.

Cayley's next papers on aerial navigation appeared in *Tilloch's Philosophical Magazine*, the famous *Phil.*

*Miss E. C. Pike has commented that this involves the assumption of a lift/drag ratio of 15 for the complete aeroplane, when flying at the speed for minimum power.

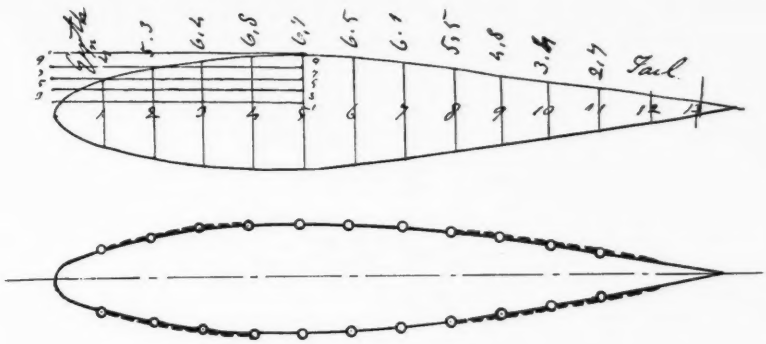


FIGURE 12. (*Top*) Solid of least resistance. Sketch by Cayley. (*Below*) N.A.C.A. aerofoil 63A016-LB N-0016, *see* text.

Mag. of today, in February and May 1816. In these papers he discussed the airship, its construction and performance. In his February paper he referred to his papers in *Nicholson's Journal.* "My object was to leave out the unwieldly bulk of balloons altogether, and to make use of the inclined plane propelled by a light first mover. Although my attention has hitherto been diverted from making further experiments, I am fully convinced that this mode of aerial navigation is practicable, and will, ere long, be accomplished. In the meantime I shall be glad to promote any promising experiments upon the steerage of balloons."

Cayley had a mind uncontaminated—if that is the proper word, or should it be undiluted?—by the modern complications of Mach number, skin friction, laminar flow, vortex streets or sound barriers. He went directly to the fundamental issues as he saw them.

"In considering the means for obviating the relative resistance of balloons in passing swiftly through the air, the leading general principle is evidently to increase their dimensions far beyond the limits hitherto adopted. The weight of their superficial materials, and the resistance they meet with, being as the squares of their diameters, whereas their power of support being as the cubes of these diameters, it follows that their power may be made to bear any required proportion to their resistance. Thus a balloon of one yard in diameter meets with ten times more resistance, in proportion to its power, than a balloon of ten yards in diameter.

"A globe is by no means the best shape for obviating resistance: a greater extension in the line of its path, with a corresponding diminution in the section perpendicular to it, may be adopted with great advantage."

In his notebook he had drawn attention to the trout as offering the best streamlined shape. He suggested that if such a solid were cut in halves along its longitudinal axis, "we should then be deriving our boat from a better architect than man, and should probably have the real solid of least resistance."

von Kármán in his *Aerodynamics* published in 1954, has drawn attention to the astonishing fact that Cayley's outline, "almost exactly coincides with certain low-drag airfoil sections." Fig. 12 shows Cayley's sketch taken from his Notebook, and for comparison aerofoil section N.A.C.A. 63A016-LB N-0016. The circles indicate Cayley's points superimposed upon the aerofoil section, as shown in von Kármán's book.

In his paper of February 1816 Cayley discussed a proposal which had been put forward in the *Philosophical Magazine* by a Mr. John Evans, for steerable balloons.

"Mr. Evans," he wrote, "proposes the action of a large inclined plane suspended below a common balloon, as the means of making it take an oblique course in its ascent. . . . This principle is unquestionably capable of performing what that gentleman proposes."

Evans proposed a Montgolfier hot-air balloon of 80 ft. in diameter with an oblong plane surface suspended below it at an angle of 70° to the vertical. The length of the plane was $1\frac{1}{2}$ times the diameter of the balloon and its width that of the balloon. As the balloon rose, the horizontal component of the force of the downward air stream on the inclined plane provided the power to move the balloon forward. Evans reckoned the vertical speed of the balloon at 28 ft. per second and the horizontal speed at 15·4 ft. per second.

It was an ingenious idea. It seems clear, nevertheless, that although in a dead calm there was a possibility of steering a balloon by this method, the difficulty of control of the inclined plane would probably lead to a rotation of the balloon, and soon all control of direction would be lost. In a wind, indeed, control must rapidly be lost since the inclined plane would be subject, if the balloon began moving in any other direction than that of the wind, to a force on the plane opposing that caused by the ascent of the balloon. There would, at the best, be an uneasy control about the position of equilibrium, and an oscillation would arise more quickly than it could be damped.

As Cayley did not believe that a globe was the best shape "for obviating resistance," he wanted experiments to be made on elongated balloons. Like Evans, he chose hot air as the cheapest way for airship experiments, "and," he wrote, "upon a large scale with proper precautions it may be made safe with respect to fire. . . . The scale I propose to adopt, though as small as compatible with the object in view, will appear to any one who has not calculated the proportions required for the success of the experiment, of stupendous magnitude.

"Amazement would have been the consequence of presenting to the imagination of an ancient Briton the idea of a British hundred-gun ship, when only contemplating the principles of navigation exhibited in his humble coracle covered with a skin. From the truck

of the flag staff to the extreme of the bowsprit, a vessel of this sort will measure about ninety yards; and it is a wonderful effort of human ingenuity arising from the gradually accumulating knowledge of ages: but the *long boat* of aerial navigation commences about the bulk where the man-of-war of common navigation has reached its full growth; and what may be the vessels, *I hope not men-of-war*, of this sort which a thousand years of human invention may bring to light, I am at a loss to contemplate."

Cayley contemplated well enough when he insisted, as he did in later papers, that an airship to be successful, must be large, larger indeed than any battleship. It was the tremendous cost of building such a vessel which led him to suggest experimenting on as small and as cheap a scale as possible, so that the necessary experimental data could be obtained. Even then his proposed experimental airship was not small in reality. It was 300 ft. long, 90 ft. wide and 45 ft. maximum height. The car was slung 80 ft. below the ship, which was open underneath, like an up-turned boat, and braced to hold its shape. The car held a fire grate from which rose a tall chimney to convey the heated air to the airship framework. A rudder *D* (*see* Fig. 13) enabled the airship to be steered, once steerage way had been obtained.

"The machine being thus completed, so far as it is necessary to try the principle of the *inclined* plane," wrote Cayley, "as soon as the balloon is inflated, let the front ropes be lengthened and the hinder ones shortened, till it stands at an angle of about 30° to the horizon, when it will be found to rise in an angle of about 45°, and the horizontal velocity towards its destined harbour will be about 20 miles an hour."

Cayley, in his paper, gives the necessary calculations and assumptions on which he based the performance of his proposed airship. He fell back again upon the assumption that the resistance to forward motion is one pound for every square foot of the greatest cross section of the airship and "the power of the heated air (that is the lift) would be about 17,600 lb.; of this about 6,800 lb. would be required to generate the velocity specified, and the remainder will be consumed in the weight of materials, fuel, passengers, etc.

"The exterior resistance of the air to the anterior portion of the balloon, will amount on some parts of it to about 26 lb. per sq. yd. at the proposed speed; and hence an internal pressure of at least equal to this must be created, for the purpose of preserving the form of the balloon."

In this Cayley saw the importance of preserving the shape of the airship against the external pressures with which it was bound to contend. This was probably the first time that attention was drawn to this point.

It is of historic interest to quote Cayley on the fuel problem with which he was faced. It should always be remembered that he was not proposing this airship as a prototype, but merely one for experimental purposes. He was all the time very much concerned with finding a light engine for its power. Although the existing steam engine was far too heavy even to think about for an aeroplane, it was a possibility for an airship, for the weight of fuel for a steam engine, *i.e.* water for steam and coal for heating, was very much less per horsepower than for the fuel to heat a hot-air airship.

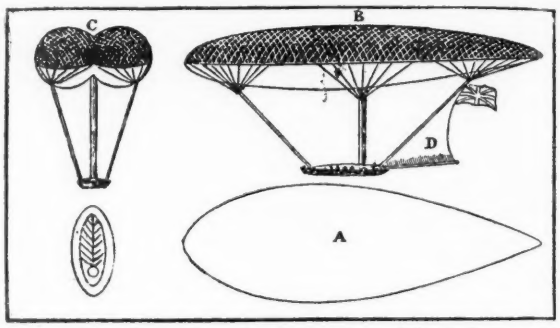


FIGURE 13. Plan, side and end elevation of Cayley's steerable Montgolfier balloon.

"If the specific heat of air be to that of water as 1·79 to 1," wrote Cayley, "it will require about 880 lb. of fuel to inflate this balloon, exclusive of what will be consumed to supply the waste of heat during the operation; and when a second rise is required, by having suffered the escape of air equal to the power of 6,800 lb., it will require the rapid combustion of 340 lb. of shavings, chopped straw, and so on, to create a new ascent. Hence, including waste, probably about 100 lb. of fuel will be expended for every mile of conveyance, exclusive of the first inflation."

Today, as every day when a new method of transport is born, the early economic shock of pessimistic accountants forces constant attention to be paid to fuel savings, weight per horsepower of engine and fuel, over a given range. Cayley was as weight conscious as any modern designer. Indeed, following his fuel note just quoted, he stated that if this experiment proved successful then "it will be easy to try whether the balloon can be driven directly forward by sails wafted by the steam engine at a less expense of fuel."

The hot-air airship climbed at an angle and hence Cayley's remark about testing the principle of the inclined plane. He discusses the fuel position and points out that with the proposed hot-air balloon or airship, in order to reach a given position in a horizontal direction, two sides of a right-angled triangle have to be covered, whereas with a steam-engine and some method of horizontal propulsion, the vessel could make the journey direct.

Crude as were these suggested preliminary experiments by Evans, Cayley and others, they showed clearly that a proper appreciation of the problem was being made, and the suggestions for experimental research lay within the sphere of knowledge of that time. Cayley not only played a leading part in trying to promote the airship, but he showed more ability to understand the principles involved than did most of his contemporaries. He was anxious that no idea which held out any prospect of success, should be left untried and he strongly deprecated those who jockeyed to obtain credit for themselves.

"For my own part," he declared satirically, "I shall sue for no share in the scramble respecting Montgolfier balloons, but that of braving the risible muscles of my

friends in substituting *acres* for *yards* of cloth in their structure, unless it be for the addition of a *chimney*, a most common, natural, and in this case particularly useful appendage to a fire. I shall, however, be extremely grateful to claim the credit of standing on the same list as Mr. Edgeworth as a subscriber towards completing this noble art."

This last statement was a reference to a suggestion that a fund should be raised to pay the cost of the proposed experiments.

In his paper of May 1816 Cayley, in view of some of the criticisms which had been made of his proposals, added further practical details for carrying them out. He at once refuted the suggestion that he had been extravagant in his ideas about the proper size for an airship. "Indeed," he retorted, "the unwieldly bulk of these bodies is unwillingly thrust upon me by the result of calculations grounded upon the facts of the case."

He discusses the use of hydrogen.

"The danger attending the hydrogen gas balloon, where any first mover is used that acts by fire, is a great obstacle to their introduction. . . ."

But if hydrogen were used Cayley pointed out that it would be necessary to lessen the leakage as much as possible, not only on account of cost but to keep up the internal pressure in order to resist the external pressure on the envelope while in flight.

"This would oblige a double structure, one of thin oiled silk containing the gas, and one of a coarser texture surrounding it, which would receive the condensation (a word used by Cayley for pressure) necessary from common air driven in occasionally by a pump; or perhaps with some little contrivance an aperture at the point of the prow, receiving the full direct resistance of the external air, commensurate with the velocity of the balloon, would answer the purpose."

With regard to the danger from fire, Cayley wrote, "It was my intention to have ascertained what proportion of azote (an early name for nitrogen) with hydrogen gas would render it incombustible on its access to common air; but owing to an accident in the experiment immediately previous to my leaving home, this must be reserved to a future opportunity: perhaps the adulteration required may be so great as to render the specific gravity of the mixture too nearly the same as the atmospheric air to be of any use in this instance."

In this second paper Cayley proposed an airship 432 ft. in length. He reckoned the total lift to be 163,000 lb. He allowed 41,000 lb. for structure weight, leaving some 50 tons for the steam engine, fuel, cargo and crew and passengers. In an interesting footnote, Cayley gave an estimate of the weight of an expansive steam-engine of 100 h.p. with fuel and water for an hour's flight as 15,210 lb. and states, "Upon estimating the probable weight even of steam engines on a large scale, it appears that 160 lb. per horsepower is an ample allowance with its load of coal and water for one hour; and as the water is a considerable part of the whole, and can be recovered for the use of the engine by permitting steam to pass within the double coats of the balloon, and to be thus exposed to so extensive a cooling surface, it is probable that 200 lb. per horsepower will be more than sufficient for working twelve hours without any further supply of water or fuel."

This was a remarkable suggestion, here made for the first time in airship history as far as I can ascertain, for water recovery in an ingenious way, for saving fuel and incidentally ballast.

"I shall deduct three times the weight of the engine estimated in the note," added Cayley cautiously, "when there will remain rather more than 34 tons of power (*i.e.* lift) for any purpose required. This would convey 500 men during one hour, 410 men for 12 hours, 290 men for 24 hours, and 50 men for 48 hours, without fresh supplies of fuel or water. The extent of the voyage in calm air would in the latter case be 960 miles."

Cayley had calculated throughout for a speed of 20 m.p.h.

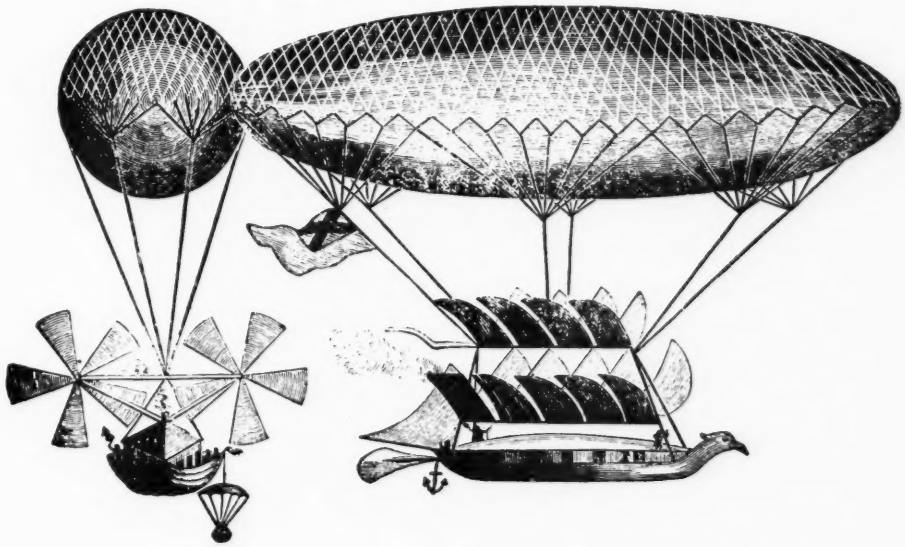


FIGURE 14. Balloon driven by airscrews and Cayley's airship driven by movable planes.

"I do not offer this statement with any expectation of its being realised in our age; but I do affirm," he declared, "that balloon navigation does hold out the capabilities I have so daringly ventured to investigate. . . . The vast strides which science of every kind has made within the last twenty years renders every advancing step more easy; and it appears to me that England may soon have the honour of perfecting the construction of balloons although the invention of them was not altogether her own."

Just over a year later, in a third article in the *Philosophical Magazine*, for July 1817, Cayley expressed disappointment that sufficient funds had not been found to carry out an experimental investigation into the possibilities of airships and suggested the formation of a small committee from among the subscribers to such a fund, so that they were safeguarded and could be sure the money subscribed was actually being used on airship research.

Cayley made the suggestion that the propelling power should come from moving planes driven by a steam engine, although Evans had expressed the thought that airscrews would be better.

"I prefer the wing plan as the easiest for our first experiments," replied Cayley. "Mr. Evans may see in my early papers upon this subject that revolving flyers had not escaped my attention; indeed, the first experiment I made upon the mechanical principles of aerial navigation, was successfully executed, though on a very small scale and by very simple means, upon this very plan."

Cayley was fully aware of the advantages of the airscrew, but, in his first experimental effort with the airship he thought "the wing construction offers an advantage of great importance—that of providing, if properly managed, a safe descent in case of accident to the balloon." (Fig. 14).

Cayley replied to further criticisms in his third paper, and added an interesting statement on the mooring of airships in winds.

"The relative power of balloons to break away from their anchorage in a storm of wind, decreases under the circumstances of magnitude and oblong structure I have proposed, in the same ratio with the decrease of their resistance in passing through the air. The horizontal drag of the balloon of 50 tons when at anchor, and exposed to the various degrees of wind in Mr. Smeaton's table will be as follows:—

Wind	*m.p.h.*	*horizontal drag*
High	32½	8 tons
Very High	42½	13½ „
Storm or Tempest	50	19 „
Great Storm	60	27 „ "

Cayley pointed out that airships would have to be strongly constructed and braced by a wide net of cordage to withstand the pressures and added, "It will be necessary to make them in several compartments, like the stomachs of a leech. . . . .The necessity of having several compartments in large balloons, though an evil in weight, is fully compensated for by the additional security it bestows: by this structure, an accidental rupture of one portion would not cause a precipitate descent." (Fig. 15).

Cayley here was making a further fundamental suggestion in the construction of airships, the separate internal balloons which are essential for airship construction, not only as a precaution against accidental rupture, but, as Cayley was not aware, the dangerous surging of such a large quantity of gas if not controlled.

Like so many of the early aeronautical pioneers, Cayley was destined to suffer the disappointments of being a pioneer. Money was not forthcoming for experimental research, and it was not until 1837 that he returned to the attack, in the *Mechanics Magazine* for 4th March of that year. In this paper he largely recapitulates the arguments of his three papers of twenty years previously, and again he emphasises the principle that the airship must be large to be efficient.

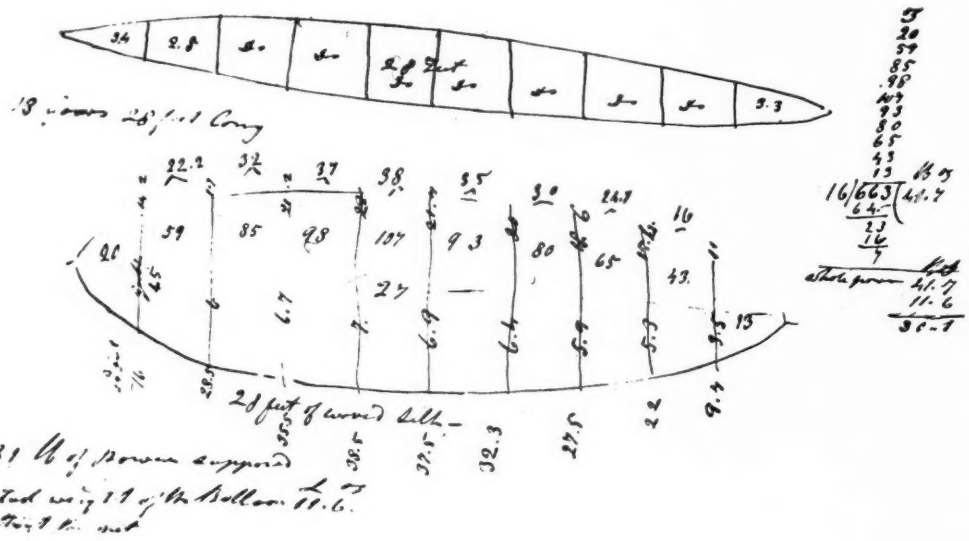


FIGURE 15. Cayley's outline drawing of a model airship 28 ft. long, divided into sections showing lift in each in ounces. The whole lift was reckoned as 41·7 oz., and weight of structure 11·6 oz.

"The age was not ripe for the subject," he wrote. "Steam boats were in their infancy, and railway velocity unknown; twenty miles an hour seemed then monstrous and chimerical; now our only fear is that balloons will not have the speed enough to satisfy our locomotive mania."

In this later paper he discusses the resistance of balloons and airship shapes and "as experiments are scarce upon this subject . . . I made a light case of papers, glued together over a truly spheroidal mould 18 inches long by 6 inches in diameter, and loaded it so as to fall through the air in the line of the larger axis. A circle of 6 inches diameter was then loaded till it fell with equal velocity, keeping perpendicular to the line of its fall. The weight required to drag the flat circle with equal speed, side by side, through a fall of 30 feet, was 4·8 greater than that of the spheroid (of course the *whole* weight of each apparatus was thus the measure of the resistance)."

Cayley devotes part of his 1837 paper to a discussion of various means of propelling an airship, of which means the following must surely be of interest today to all those who disagree with Henry Ford that History is Bunk, and to those who still firmly believe that History repeats itself.

"Communicating centrifugal force to air by means of a hollow drum and fans by the steam engine, is another means of getting a propelling power conveniently applicable in every direction that may be required; for by having a movable mouthpiece, from which the air escapes, the re-action will always be in the opposite direction."

The turbo-jet is, I understand, a very successful modern means of propulsion for aeronautical vessels of large sizes.

On 29th September 1842, W. S. Henson took out his famous patent for a "machine for conveying letters, goods and passengers from place to place through the air." In a few months his ideas were exploited by company promoters who sought Parliamentary powers for an Aerial Steam Transit Company. Henson's Aerial Steam Carriage was shown in prints, plain and coloured, flying over London and Egypt and India and China as the great new wonder of the age. It was a monoplane of 150 ft. span and 30 ft. chord, giving a surface of 4,500 sq. ft. It was powered by a steam engine driving twin pusher airscrews, and had a large triangular tail.

In the *Mechanics Magazine* for 8th April 1843 Cayley criticised Henson's project at some length.

"The magnitude of the proposed vehicle will, I much fear, militate against its success," he wrote. After pointing out that the weights of birds increase as the cubes of their linear dimensions, while the surface of their supporting wings only increase as the squares, he criticised the great span of Henson's machine. "The extent of the leverage, however well guarded by diagonal braces, is in this necessarily light structure, terrific. For, although the wings are not intended to be wafted, the atmosphere, even in moderately calm weather, near the earth is subject to eddies; and the weight of the engine and cargo in the central part of this vast extent of surface, would, in the case of any sudden check, operate with enormous power to break the slender fabric. . . .

"This consideration shows, that in order to obtain a sufficient quantity of surface to sustain great weights in the air, the extension ought not to be made in one plane but in parallel planes one above the other at a convenient distance, so as to form a more compact fabric

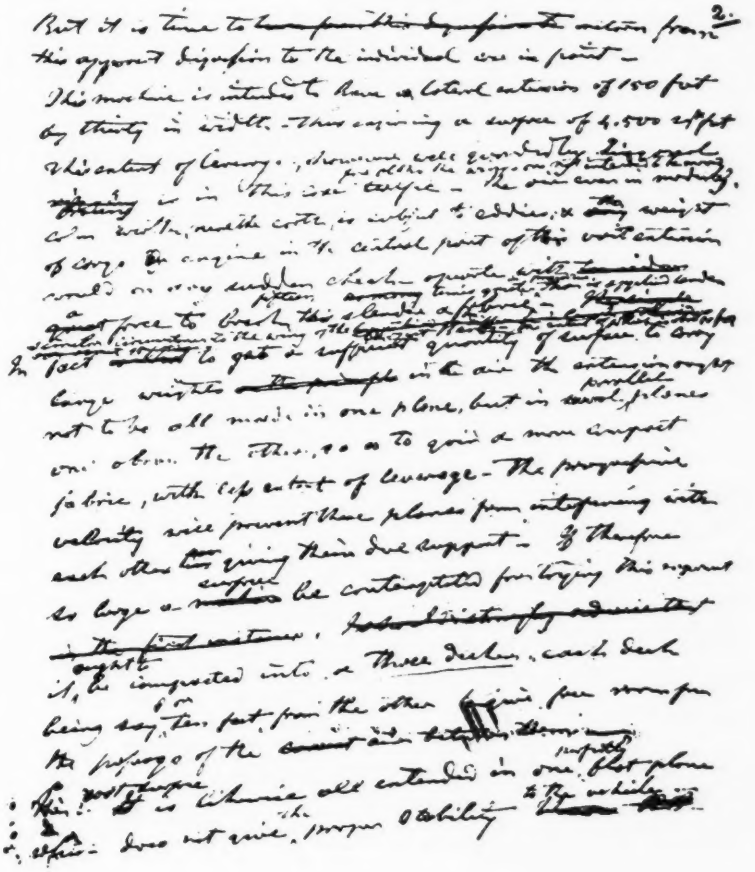
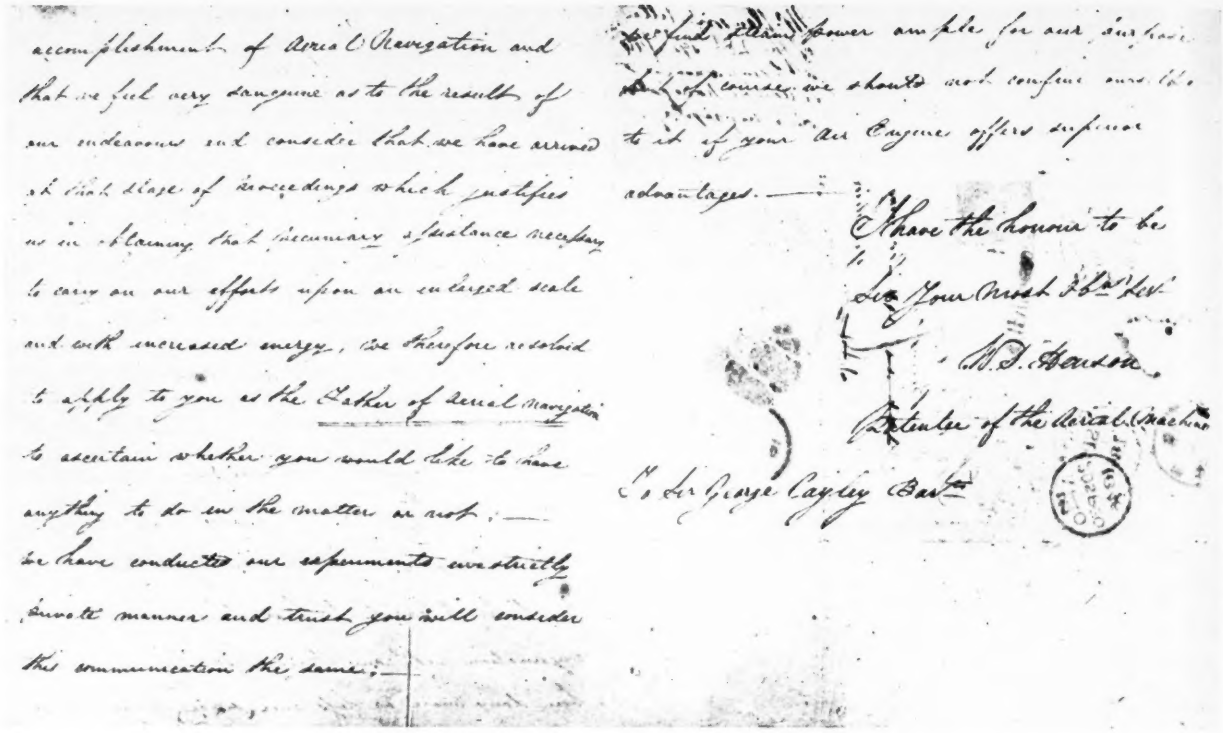


FIGURE 16. MS of part of 1843 paper of Cayley's on Henson.



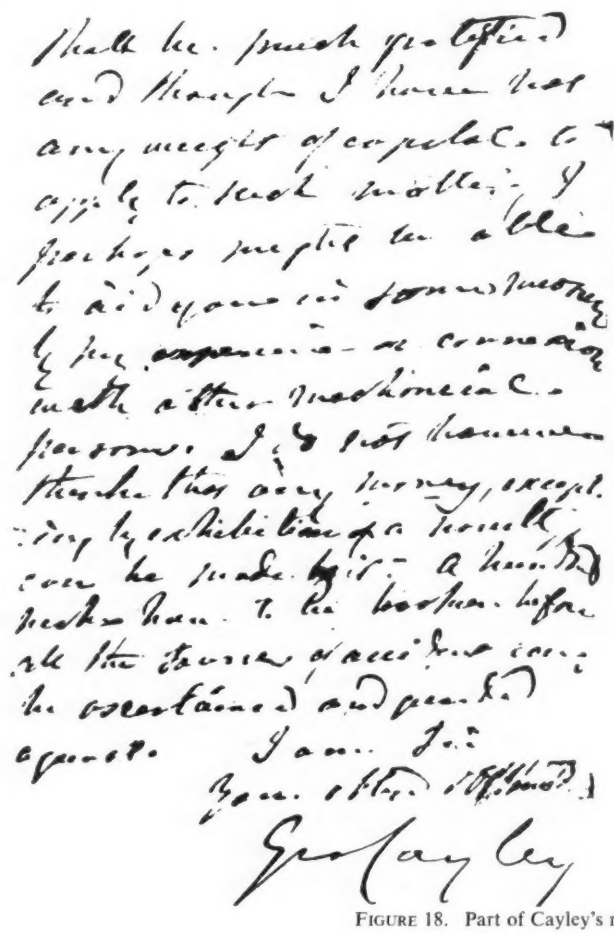
accomplishment of Aerial Navigation and that we feel very sanguine as to the results of our endeavours and consider that we have arrived at that stage of proceedings which justifies us in planning that pecuniary assistance necessary to carry on our efforts upon an enlarged scale and with increased energy, we therefore resolved to apply to you as the Father of Aerial Navigation to ascertain whether you would like to have anything to do in the matter or not.—
We have conducted our experiments unostentatiously & in a private manner and trust you will consider this communication the same.—

powerful steam power ample for our purpose. Of course we should not confine ourselves to it if your Air Engines offers superior advantages.—

I have the honour to be
Dear Your most Obt Servt
W. S. Henson
Patentee of the Aerial Machine

To Sir George Cayley Bart

FIGURE 17. MS. of Henson's letter to Cayley in which he refers to Cayley as the Father of Aerial Navigation.



... I had thought that you had abandoned the subject, which, tho' true in principle, you had rushed upon with far too great confidence as to its practice some years ago.... I perhaps might be able to aid you in some measure by my experience or connexion with other mechanical persons. I do not however think that any money, excepting by exhibition of a novelty can be made by it. A hundred necks have to be broken before all the causes of accident can be ascertained and guarded against.

I am Sir

Your obliged and obedient

Servant

George Cayley.

FIGURE 18. Part of Cayley's reply to Henson's letter.

. . . would it not be more likely to answer the purpose to compact it into the form of a *three decker*, each deck being 8 to 10 ft. from the other, to give free room for the passage of air between them?

"This vast surface is all extended in one nearly horizontal plane, which is not the form experimentally proved to give the lateral stability to the machine. It was remarked in my last letter, that the surface should be made in the form of the letter V, though of a much more obtuse angle."

In the autumn of 1846 Henson wrote from Chard, Somerset, to Cayley, "You probably imagined that I had long since given it up as a failure, and you will no doubt be pleased to hear that I have, in conjunction with my friend Mr. Stringfellow, been doing more or less ever since 1843 towards the accomplishment of aerial navigation, and that we feel very sanguine as to the result of our endeavour and consider that we have arrived at that stage of proceedings which justify us in obtaining that pecuniary assistance necessary to carry on our efforts upon an enlarged scale and with increasing energy. We therefore resolved to apply to you as the Father of Aerial Navigation. . . ."

To which Cayley replied that he had "ever felt a great interest in the subject of aerial navigation, which has most certainly to mark, at some time one great era in the progress of human improvement. . . . I thought that you had abandoned the subject, which, though true in principle, you had rushed upon with far too great confidence in its practice some years ago. . . . As for new principles, there are none, of practical expedients there will soon be an endless variety and to select the best is the point at issue. . . . I do not, however, think that any money, excepting of a novelty, can be made by it. . . . A hundred necks have to be broken before all the sources of accident can be ascertained and guarded against."

Figures 17 and 18 show part of Henson's letter and Cayley's reply.

As far as I am aware this 1843 paper of Cayley's has never been reprinted, in English, although a translation was published in the Bulletin of the Société Aerostatique et Météorologique de France ten years later. It is a paper which throws a considerable light on his ideas, and I quote freely from it. Fig. 16 shows part of Cayley's original manuscript of the paper.

"Aerial navigation by mechanical means alone, must depend upon surfaces moving with considerable velocity through the air . . . they must be capable of landing at any place where there is space to receive them, and of ascending from that point. They should likewise be capable of remaining stationary, or nearly so, in the air, when required.

"Very great power, in proportion to the weight of the engine, is necessary to answer these, or, indeed, any of the purposes of aerial navigation by mechanical means alone. . . . There can be no doubt that the inclined plane is the true principle of aerial by mechanical means. . . . The larger the surface in proportion to the weight, the less velocity it requires for support."

Cayley suggested that large airships will offer "the most ready, efficient and safe means of aerial

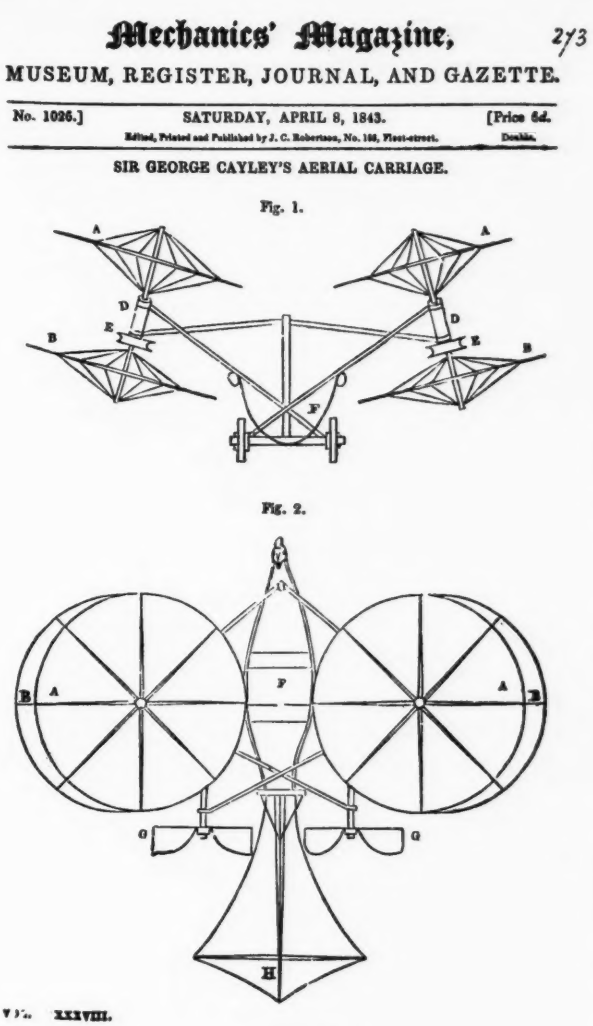


FIGURE 19.

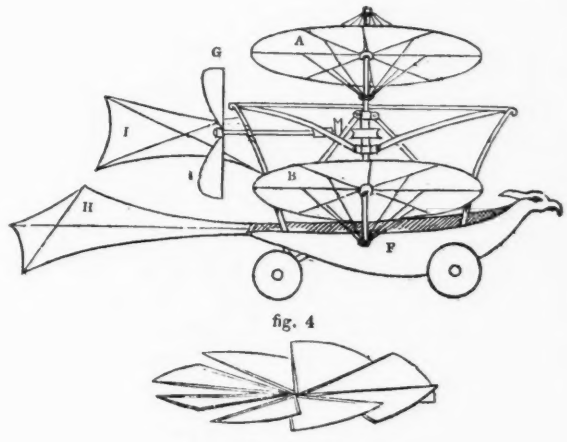


FIGURE 20.

FIGURE 19 and FIGURE 20. Sir George Cayley's Aerial Carriage.

navigation," quotes his paper of 1837, and then returns to a discussion of a new way of obtaining the necessary lift and speed. It is then that the significance of his words in the last two paragraphs become clear.

"Figures 1, 2 and 3 (of Figs. 19 and 20) will exhibit, without tedious explanation, the construction of an aerial vehicle, containing 530 sq. ft. of surface. . . . The main surfaces *AA* and *BB* are here placed one above the other, and each pair are connected together by strong shafts, firmly fixed into sockets at each end of a steel axis, which turn freely in their collars *DD*. These shafts carry a spiked pulley or drum *EE*, by which they may be turned by a pierced belt, or chain, from the engine in the car *F*.

"The construction of these circular planes is such that when only required as a stationary expanse of surface, they continue in one even, or rather slightly curved state, like a very flat umbrella; but when the engine power is applied, to make them revolve in their proper directions, one set adverse to the other, they are immediately by that act, thrown open, into the form of the flier Fig. 4 (of Fig. 20), and thus the surface, to a great extent, is made to skim, though the machine may be stationary—the upper edge of each section in these fliers being foremost. It must also be observed, that the two sets of fliers are placed in the obtuse V form to ensure lateral steadiness to the machine. These may be termed the elevating fliers, to distinguish them from the two other smaller ones *GG*, set at a very different angle with their axis, and used for propelling the machine, when the others are stationary; both sets will be put into action gradually, or in any required degree by friction plates, as is usual in such cases."

The mechanics of Cayley's suggestion may be difficult, but his proposal contains all the performance ideas for the convertiplane—the revolving blades *AA* and *BB* for take-off, and the airscrews *GG* for horizontal flight; *AA* and *BB* becoming fixed surfaces. Note the contra-rotating fliers to eliminate torque, and the movable horizontal tail and rudder. This is Cayley's machine capable of "landing at any place capable of receiving it, and of ascending from that point," and "capable of remaining stationary, or nearly so, in the air."

"The small vertical rudder *I*," continued Cayley, "is for the purpose of lateral steerage, in combination with

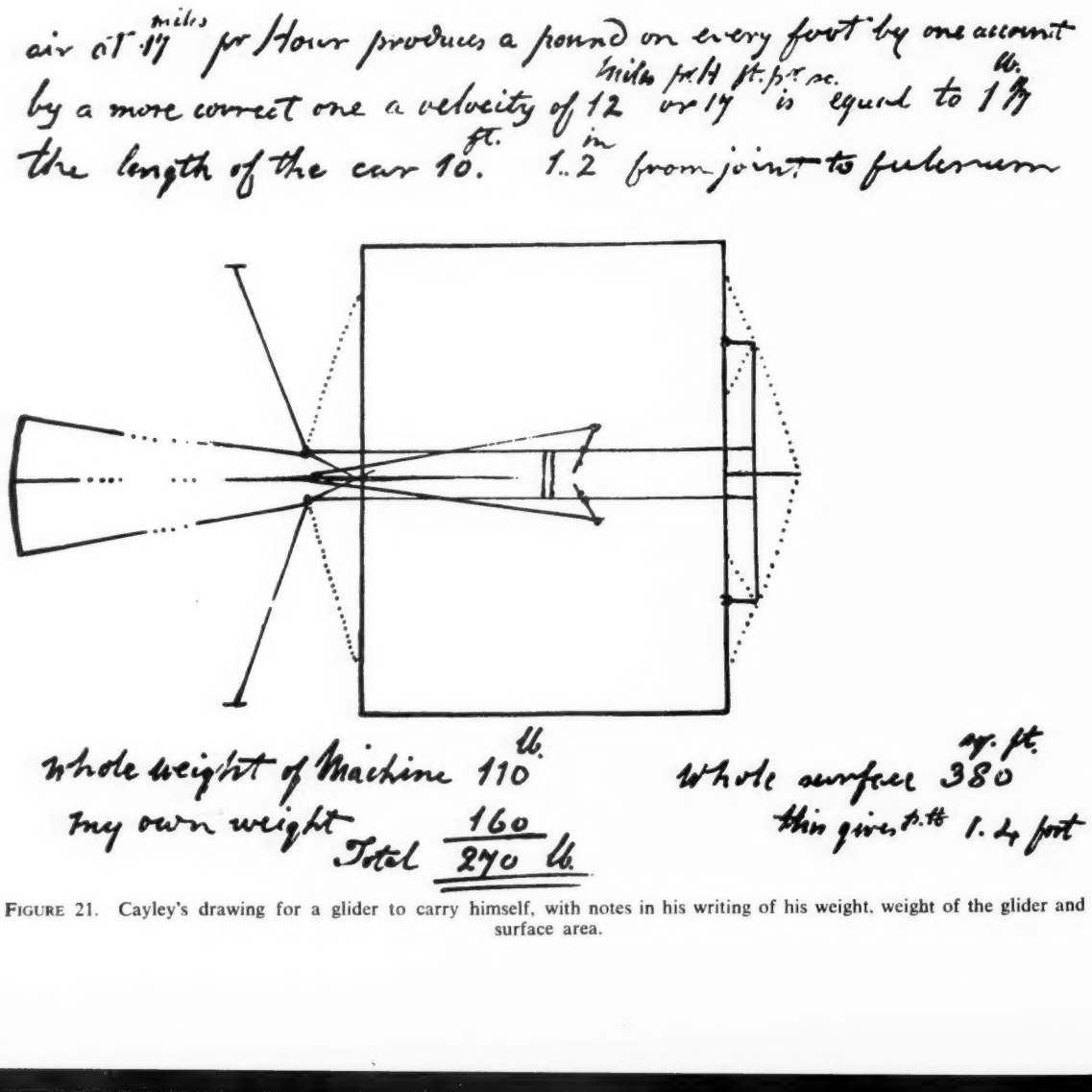

air of 17 miles per Hour produces a pound on every foot by one account
by a more correct one a velocity of 12 miles per Hour or 17 ft. per sec. is equal to 1 lb.
the length of the car 10. ft. 1..2 in from joint to fulcrum
Whole weight of Machine 110 lb.
my own weight 160
Total 270 lb.
Whole surface 380 sq. ft.
this gives p. lb 1. 4 foot

FIGURE 21. Cayley's drawing for a glider to carry himself, with notes in his writing of his weight, weight of the glider and surface area.

the two propellers, which, by being used singly, will turn the machine with great power; and if one be reversed by the same means as those now used for steam paddles, a still greater lateral guidance can be obtained."

In this proposal Cayley showed that he understood the kind of controls which were the minimum necessary for safe flight. He set his planes at a dihedral angle and his horizontal tail was "capable of being turned on its hinge at any angle, at pleasure, gives the power of ascent or descent when the propellers are used, and forms also the chief means of stability in the path of flight."

It was not until nine years later, in 1852, that another paper by Cayley appeared in the *Mechanics Magazine* under the title of "Sir George Cayley's Governable Parachutes." He was then in his 79th year. The subject of parachutes had come into public discussion and Cayley first of all drew attention to his paper in *Nicholson's Journal*, where he had discussed the stability of parachutes. The title of this paper is somewhat misleading, as Cayley was concerned with using a glider which could be released from a balloon.

Cayley's last contribution to the science of aeronautics was one he wrote for the Société Aerostatique et Météorologique de France. It was in two parts, the first of which was the only one to be published in the Bulletin of the Society, before it ceased publication. This paper was published in Cayley's 80th year and shows the vigour of his mind to the last years of his life. In it he suggested that attention should be paid to making "some cheap preliminary experiments" to find out what could be done with plane surfaces until an engine "combining sufficient power within a certain limit as to weight, is discovered."

Cayley suggested that a man himself might provide the power for these experiments, "although the flight of man by his own ordinary strength is thus hopeless as to any useful effect, yet when a man weighing 150 pounds momentarily run up steps at the rate of 7½ feet perpendicular rise per second, he is exerting the ordinary power of a two horse steam engine; and for an experimental purpose, soon to be explained, I propose thus to apply human strength."

He proposed that the wings of his glider should be free to some extent to beat, when the pilot exerted all his strength for a brief while, through suitable mechanism, though acting as fixed wings for gliding, otherwise, as when birds glide after beating their wings. (*See* Fig. 22).

"The whole apparatus when loaded by a weight equal to that of the man intended ultimately to try the experiment," was to be launched from the side of a hill, and tested "by repeated experiments, in perfectly calm weather, for both the safety of the man and datum required." When satisfied with the experiments carried out with a dummy, Cayley suggested that "the wings be plied with the man's utmost strength," during the glide, "and let the angle measured by the greater extent of horizontal range of flight be noted, when this point, by repeated experiments, has been accurately found we shall have ascertained a sound practical basis for calculating the engine power necessary under the same

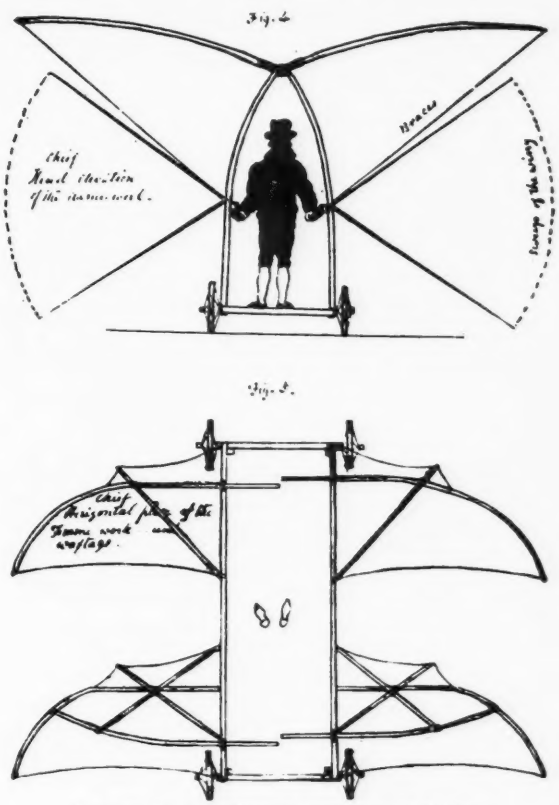


FIGURE 22. Experimental moving wing glider.

circumstances as to weight and surface to produce horizontal flight—and this is all that can reasonably be expected from the application of human strength."

One feels that if Cayley's ideas and experimental proposals had been followed up vigorously at the time, gliding might have become well advanced by the time the engine was ready. (*See* Fig. 23).

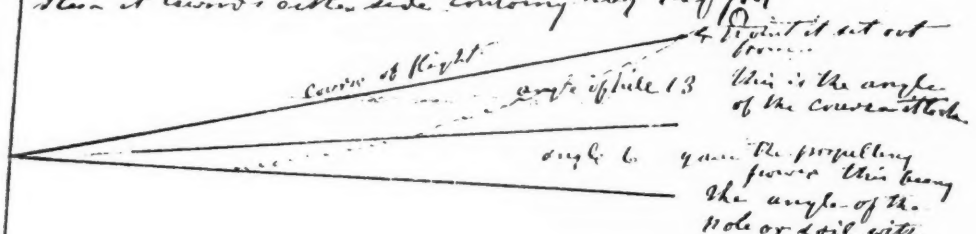
In the second and unpublished half of his paper, Cayley gives a description of some experiments he had been making to ascertain the weight carried by a surface at a given angle of incidence when gliding, and the model aeroplane he made with which to carry out the experiments. In one of these experiments, with a larger machine, he mentions that "a boy of ten years was floated off the ground for several yards on descending a hill, and also for about the same space by some persons pulling the apparatus against a very slight breeze by a rope."

Cayley drew attention to the difficulties and danger of starting the glide, and urged that gliding should "only be done on a perfectly calm day," and continued, "it requires a hill at hand, of a smooth surface and rapid descent. In fact a mound ought to be prepared purposely, say 50 ft. in length of slope with 23 ft. perpendicular rise, and then curving off to a continued descent of one in four, for some convenient distance."*

*He thus anticipated Lilienthal's artificial hill outside Berlin by a quarter of a century.

Brompton August the 30th 1849 – I tried some experiments with a view to ascertain with accuracy the real angle that any plane makes with its line of flight when supporting a given weight & also the power shown to be necessary in that line of flight to sustain that weight – The surface used was 16 sq.ft of cotton cloth tightly stretched by two yards like those of a ship's sail made flat to give little resistance to the air –

A strong pole 4½ feet long was the basis of this machine two upright pieces kept three yards 10½ inches above the pole & put the centre of gravity below the centre of support & this centre of gravity was 5 inches forwarder than the centre of support & 10½ inches below it (stood 5 inches) The whole machine weighed 16 pounds exactly – The sail contained 2½ square feet & was slightly elevated (about an angle of 8°) it had also a rudder to steer it towards either side containing say 1 sq.ft



to direct it out of the
This is the angle of the Course with the horizon
gave the propelling power this being the angle of the pole or sail with the horizon –

The velocity varied in some of the flights but the best average was at the rate of 200 feet in 6 seconds The angle varied between 190 & 210 in the six seconds –

Hence a velocity of about 33 feet at an angle of 7° with the line of path (one 8th of rodius) sustains on 16 feet 16 pounds This agrees precisely with the weight of the crow & his surface of wing

FIGURE 23. Cayley's notes of an experimental glider. "I tried some experiment with a view to ascertain with accuracy the real angle that any plane makes with its line of flight when supporting a given weight and also the power shown to be necessary in that line of flight to sustain that weight. The surface used was 16 sq. ft. of cotton cloth tightly stretched by two yards like those of a ship's sail made flat to give little resistance to the air. . . . The velocity varied in some of the flights but the best average was at the rate of 200 ft. in 6 seconds. . . . Hence a velocity of about 33 ft. per second at an angle of 7° with the line of path sustains on 16 ft. 16 pounds. This agrees precisely with the weight of the crow and his surface of wing."

These experiments must have been made in 1852 or 1853, according to Mrs. George Thompson, Cayley's grand-daughter.

The glider was being tested at Brompton Hall. The field there, sloping on two sides, was naturally suited for these early gliding experiments. Mrs. Thompson relates, "Everyone was out on the high east side and I saw the start from close to. The coachman went in the machine and landed on the west side at about the same level. The coachman got himself clear, and when the watchers had got across he shouted, 'Please, Sir George, I wish to give notice. I was hired to drive, not to fly.'"

This second part of Cayley's paper concluded with a special appeal to the French Society to "occupy itself, under a scientific committee, with *experimental results*, rather than theoretical discussions."

In 1855 he wrote his last aeronautical paper, a description of the Improved Flying Top already noted. Two years later, on 15th December 1857, he died at Brompton Hall.

For over 60 years of his long and vigorous life Cayley never lost interest in trying to solve the problem of flight. His position in life called for constant activity and attention to other matters, as the local squire, as a leading member of a number of scientific societies, and as an influential figure in political and social spheres.

This account has been far too brief to pay full tribute to a remarkable man and it may well be asked, where does Cayley really stand in aeronautical progress? That is a question for others to answer. The Americans, the Wright Brothers, T. von Kármán and others; the Frenchmen, Alphonse Berget and Pierre Leglise; the British pioneers who discussed aeronautics so heatedly and eagerly in the second half of the nineteenth century in the annual reports of the Aeronautical Society of Great Britain; J. L. Nayler, the Secretary of the Aeronautical Research Council, and others who should know, have no doubt where he stands, one who is more than worthy of the proud title bestowed upon him by Henson, "The Father of Aerial Navigation."

Cayley was not only a pioneer and a prophet, but, so far as heavier-than-air craft were concerned and, indeed, aeronautical science in general, he was far ahead of his contemporaries, who thought in terms of bird flight and wing flapping. Leonardo da Vinci's ideas were then known to a very limited circle and were not known at all until Napoleon brought the MSS to Paris in 1798.

Cayley was the inventor of the glider, and that alone would rank him high in the history of aviation. But like many pioneers who relied upon experiment and practice to obtain the data for their fundamental conceptions, Cayley obtained no recognition from the pure scientists. He wrote, for example, to Sir Anthony Carlisle in 1810 and asked how the scientific world was regarding aerial navigation. "You ask about the opinions of the learned —I can only give you a bad report. Nicholson's two Journals have laid on Sir Joseph's table for two successive Sundays, with your paper uncut," replied Sir Anthony. Sir Joseph Banks was the President of the Royal Society at the time.

Cayley himself, in a letter to Lord Mahon, in 1809, had written, "The art of flying, or aerial navigation as I have chosen to term it for the sake of giving a little more dignity to a subject bordering upon the ludicrous in public estimation"—an indication of the view widely held at the time.

I cannot close this part of the paper without paying a tribute to John Edmund Hodgson, an Honorary Fellow of the Society, and for so long its Honorary Librarian. To him the Society owes much for the tributes he paid to Cayley in his lecture to the Society on its 70th birthday, as for his editorship of Cayley's Notebook for the Newcomen Society. The research work which Hodgson did, both before and after his discovery of the Cayley papers in 1933, opened up a path along which I have walked in his footsteps, guided by sure signposts.

And because I have also passed along some untrodden ways, I have been able to chronicle some things which have not been noted in aeronautical records, things which help to fill in a picture of a great Yorkshireman.

PART III—THE MAN

"A man's real life is that accorded to him in the thoughts of other men by reason of respect or natural love."
JOSEPH CONRAD.

The quality of a man may be judged in many ways. His recorded achievements provide only one, for how misjudged in history would Nelson have been if Lady Hamilton had never been taken off the secret list, or Napoleon if Josephine had been put on it?

Sir George Cayley married Sarah Walker, the beautiful daughter of his mathematical tutor, in 1795, and lived happily ever afterwards, although his wife had a bit more of a temper than most people. Yet it is not given to every wife, however sweet-tempered she may be, to receive from her husband on her eightieth birthday, the tribute Cayley paid to his wife on 7th April 1853. On that day he wrote a birthday ode which began,

"Full many a pleasing, many an anxious thought
This lengthened day of eighty years has brought."

and after spanning the long years of their married life, ended,

"In these chaste views our hearts can still unite—
The rising morn outshines the coming night."

Cayley was fond of writing sentimental and doggerel verse. The former pleased the ladies by their graceful

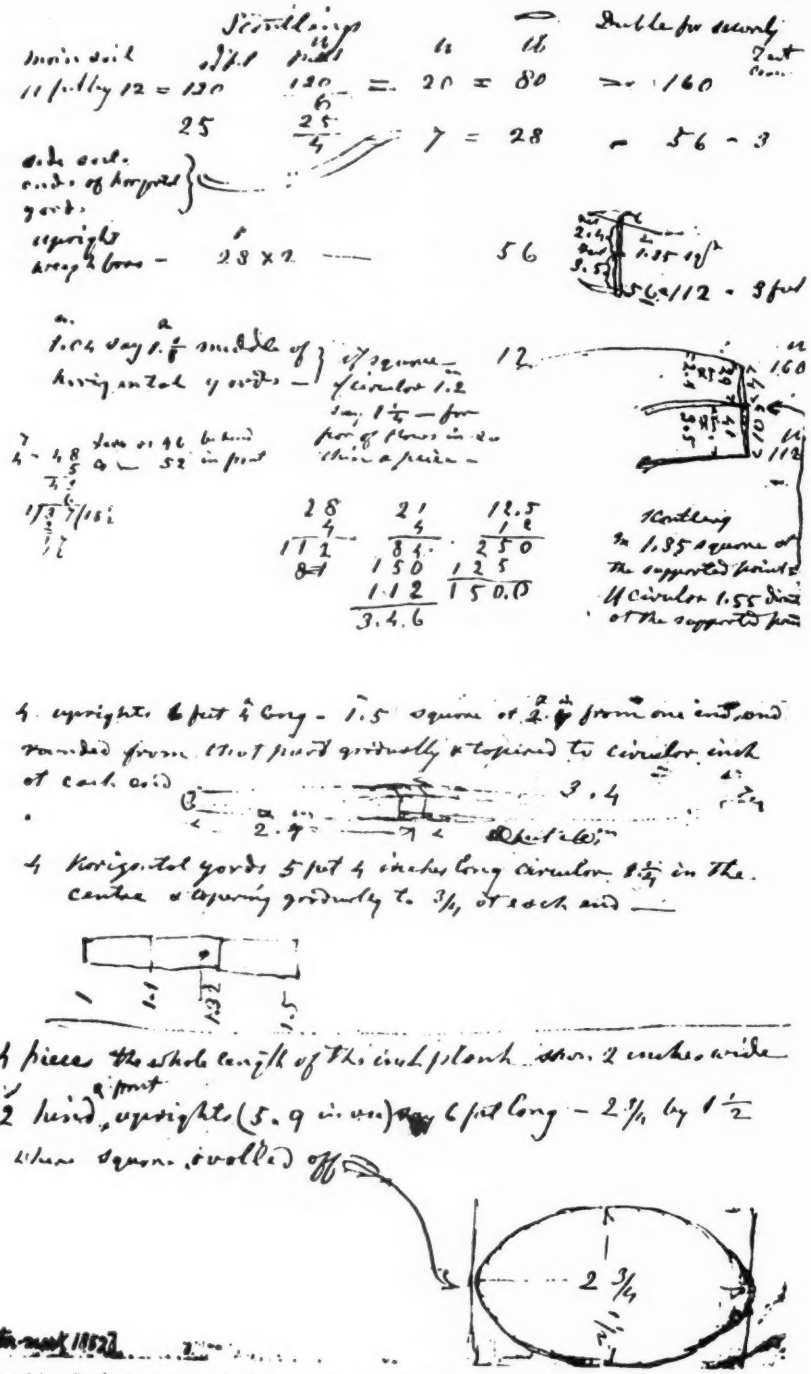


FIGURE 24. Cayley's detail calculations of strength of struts, against which he writes "double for security." Note that square struts are "ovalled off," *i.e.* streamlined, to reduce drag.

tributes, while the latter was usually of the rather flowery type which was characteristic of the first half of the nineteenth century. The Death of the Duke of Wellington, a Christmas Tree, On a Lady being affected by violent headaches—the occasion called forth the verse.

Nevertheless, Cayley had a good sense of humour. Once he gave his doctor, in an envelope, two peppermint lozenges in mistake for two golden guineas. The following day the doctor received his proper fee with the lines,

"The fee was sweet. I thank you for the hint.
These are as sweet. They've both been through the Mint."

Sir George Cayley succeeded his father when he was only nineteen. At that age he was all on the side of liberty and openly expressed himself in favour of the French Revolution. But the savagery into which it fell cured him of Republicanism. He became a Whig and did what he could, throughout his life, to advance the well-being of the people, although he was not prepared to give them authority until they were educated for it. He would have disapproved of much of the self-determination of the present day, for, as he wrote to a leading Whig, "Human society improves in all arts, century by century; and the ultimate perfection of representative government cannot be thrust on a State unfit to receive it."

Although returned to Parliament after the passing of the Reform Act in 1832, he remained in Parliament for a year only. Nevertheless he was a fierce patriot. He refused to vote with his fellow Whigs for Free Trade because he thought it would lead to unemployment or starvation wages.

When in 1807 there were threats that Britain might be invaded by Napoleon, he published a long pamphlet advocating a form of conscription to provide a national defence force. He advocated a call-up of one quarter of the available male population each year for twenty days' training, so that in four years' time every man in the country would have had some training in case war became inevitable.

Cayley did not simply make the suggestion. He gave careful calculations of the cost, became a Colonel of the Volunteers, and finished his appeal with words which might have been written today.

"Let us then embrace the opportunity of repose afforded to this country by the present situation of continental affairs; and assiduously rear up a bulwark, that shall either present so majestic a front as may effectually daunt our aspiring enemy; or, should he attempt to assail us, may heap deserved ruin upon his head."

Although Sir George and Lady Cayley had little opportunity to travel on the Continent during the uneasy days of Napoleon, the family went abroad in 1821 for two years and visited some of the leading scientists. His daughter recorded that he brought Cuvier a poor present of a few bones! In Paris he met Arago, de Ferussac and others interested in science. Afterwards he paid a number of visits to Paris, where he was

FIGURE 25. Sir George Cayley at the age of 70.

very popular. A man of great charm, wide interests, and of great intelligence, he had that gift of being able to mix with kings and not lose the common touch.

On his death, many tributes were paid to him. The directors of the Royal Polytechnic Institution, for which he had done so much, passed a resolution which recorded that they had lost "one to whom this establishment is deeply indebted for the advice and support afforded to it for many years, but they also lose the prestige of his name as chairman; and they desire to record their conviction that, from his position in society, his attainments as a scientific man, and his high character as a gentleman, it has been highly valuable to this Institution. They believe also that his earnest desire to diffuse and render popular a knowledge of science has been a great public good."

I finish with extracts from a letter by Sir George Cayley to Lord Stanhope in December 1817. Many people were apprehensive that navigation of the air would bring more evil in its train than good. In this letter, when Cayley refers simply to navigation, he means that of the sea and ships.

"I should agree with you, my Lord," began Cayley, "in thinking that aerial navigation should be well considered in its results to human society before it be introduced, provided I apprehend that we could all at once jump into full possession of this power; but it appears to me that there is more likelihood of its never

being accomplished at all in our age, than of our being overrun with a deluge of depredators like locusts on the wing. This art . . will in all probability have to creep slowly through a long interval of progressive improvements like all other arts. . . . Navigation had its attendant evils which were balanced by a greater good. . . . Navigation certainly produced the invasion of this country by Caesar, by the Saxons, and by the Normans; these events were evils to those who bore them, but to these very things we owe our civilization, or love of liberty, and our urbanity of manners. But for navigation we might have this day been naked savages with painted limbs and dwelling in huts. . . . A new and more extended power commensurate with the still further state of civilization, in my view of the case, presents itself. . . . Our business seems to me to be to put the practicability to the test, and never to hesitate as to the result. Your Lordship seems to think that the means of annoyance will be increased, whilst the means of defence remain the same. Surely the Defendant may use the same instrument as the Spoilant. I conceive that we are looking much too far in attempting to unravel all the workings of a power like this. Society may improve commensurately with the improvement of this power, and we do not estimate the moral influence of such improvement.

"National laws may regulate even aerial vehicles, for they must of necessity be large visible objects; their cost will be considerable, and where others can pursue by the same means, there will be a good prospect of capturing pirates as in shipping. The depredations of the hawk on the partridge are only equivalent to the greyhound on the hare."

ACKNOWLEDGMENTS

Sir Kenelm Cayley, at the suggestion of Mr. Hodgson, most generously has allowed the Royal Aeronautical Society to have the Cayley papers, including Cayley's unique Notebook, on permanent loan. Much in this memorial paper has been quoted from letters and MSS which have not been published before. Without these extracts it would not have been possible to give to Sir George Cayley that documented recognition he should have.

To Mrs. J. E. Hodgson the Society owes a real debt, for she has placed generously at my disposal all the papers and notes her husband had collected for his proposed Life of Cayley; and she has given me freely the benefit of her own special knowledge as she read this paper in typescript.

I wish particularly to acknowledge the help given to me by the librarians and their staffs of the Royal Institution, the Institution of Civil Engineers and the Royal Aeronautical Society. I must acknowledge, too, the help given to me by the Central Libraries at Leeds and Scarborough; to Mr. Cowley for his suggestions and practical help; to Sir Linton Andrews, editor of the *Yorkshire Post*, for the facilities he provided for enabling me to examine the files of the *Leeds Intelligencer* and the *Leeds Mercury;* and to Miss E. C. Pike for her help over certain technical questions raised in Cayley's papers on Aerial Navigation.

And last, but a long way from being least, I wish to thank the Council of the Society for allowing me to have the honour of giving this lecture, and for the very great pleasure and satisfaction it has been to me to do so.

REFERENCES

Published writings and speeches by Sir George Cayley.

1. Description of an Engine for Affording Mechanical Power from Air Expanded by Heat. *Nicholson's Journal.* 1807.
2. On Aerial Navigation. *Nicholson's Journal.* 1809.
3. Plan for an Improved Theatre. *Nicholson's Journal.* 1809.
4. Aerial Navigation. *Nicholson's Journal.* 1810.
5. Observations Respecting the Figure of a Drowned Man found in the Ice of the Pond in Halnaker Park, and Upon the Explanations which have been offered of that Singular Phenomenon. *Nicholson's Journal.* 1813.
6. On Aerial Navigation. *Tilloch's Philosophical Magazine.* 1816.
7. Letter on Pauly and Egg's Dolphin Balloon. *Tilloch's Philosophical Magazine.* 1816.
8. On Aerial Navigation. *Tilloch's Philosophical Magazine.* 1817.
9. Sir George Cayley's Patent Universal Railway. *Mechanics Magazine.* 1826.
10. On the Natural Zero, according to the Fahrenheit's Scale. *Tilloch's Philosophical Magazine.* 1829.
11. Letter Advocating Wooden Tires for Railway Wheels. *Mechanics Magazine.* 1830.
12. Sir George Cayley's Improvements in Railway Carriages. *Mechanics Magazine.* 1831.
13. Practical Remarks on Aerial Navigation. *Mechanics Magazine.* 1837.
14. Speech in a Discussion on Drainage. Minutes of the *Proceedings of the Institution of Civil Engineers.* 1838.
15. Essay on the Means of Promoting Safety in Railway Carriages. *Mechanics Magazine.* 1840.
16. The Cause of a truly erect image on the Retina of the Eye Appearing Inverted. *Mechanics Magazine.* 1840.
17. Essay on the Means of Promoting Safety in Railway Carriages. *Mechanics Magazine.* 1841.
18. On Wooden Tires for Railway Wheels. *Mechanics Magazine.* 1841.
19. On the Late Accident on the Paris and Versailles Railway. *Mechanics Magazine.* 1842.
20. Retrospect of the Progress of Aerial Navigation. *Mechanics Magazine.* 1843.
21. On the Principles of Aerial Navigation. *Mechanics Magazine.* 1843.
22. Contribution to the Discussion of Stirling's Paper on the Improved Air Engine. Minutes of the *Proceedings of the Institution of Civil Engineers.* 1845.
23. Description of an Artificial Hand. *Mechanics Magazine.* 1845.
24. Sir George Cayley's Railway Train Buffer Carriages. *Mechanics Magazine.* 1845.

25. Experiments on Shot. *Mechanics Magazine*. 1846.

26. Railway Buffers. *Mechanics Magazine*. 1847.

27. Artificial Limbs. *Mechanics Magazine*. 1849.

28. Aerostation—Mr. Luntley's Pamphlet. *Mechanics Magazine*. 1851.

29. Sir George Cayley's Governable Parachutes. *Mechanics Magazine*. 1852.

30. Remarks on the Use of Heated Air as a Motive Power. Minutes of the *Proceedings of the Institution of Civil Engineers*. 1853.

31. Mémoire sur le vol artificiel. *Bulletin of the Société Aerostatique et Météorologique de France, No.* 4. 1853.

32. On the Means of Supplying Some of the Uses of a Lost Hand by Mechanical Arrangements. *Mechanics Magazine*. 1856.

33. The Inundations in France. Preliminary Suggestions Relative to the Late Destructive Floods in France. *Mechanics Magazine*. 1856.

34. Suggestions for Rebuilding of Covent Garden Theatre. Reprint of Reference No. 3, in *Mechanics Magazine*. 1856.
(Of the foregoing references Nos. 2 and 4 were reprinted in the Annual Report of the Aeronautical Society for 1876, in the Aeronautical Classics 1910, and in Means' Aeronautical Report for 1895, all slightly abridged. Nos. 6 and 8 were reprinted in the *Journal* of the Society for February 1925; No. 13 was reprinted in *Aeronautics* for December 1909 and January 1910; and No. 20 in French in the *Bulletin of the Société Aerostatique et Météorologique de France* for May 1853.)

35. *Note-Book of Sir George Cayley*. (Edited by J. E. Hodgson.) The Newcomen Society. 1933.
This is the most important of the Cayley Papers. It was partly reprinted in the *Journal of the Royal Aeronautical Society* for June 1933. The Newcomen publication contains an invaluable list of the Mechanical and Technical papers, mostly unpublished holograph manuscripts. Many of these manuscripts are now on permanent loan to the Royal Aeronautical Society, and form the notes made by Cayley for many of his published papers already listed, including his first draft written in 1804 of the first paper on Aerial Navigation.
The list also gives details of over fifty important letters addressed to Cayley on aeronautical matters. Cayley's notes on the hot air engine and many letters from Sir Goldsworthy Gurney and others on the subject and also on his invention of the caterpillar tractor, the tension wheel and many other matters in which Cayley showed his interest.
No full memoir or life of Cayley can be written without reference to this painstaking list of references prepared by J. E. Hodgson.

36. Considerations on the Best Means of Calling Forth the General Strength of the Country for its Present and Permanent Defence. Miles et Baronettus. London 1807.

37. A Letter on the Subject of Parliamentary Reform Addressed to Major Cartwright, by Sir George Cayley, Bart. York 1818.

38. Speech by Sir George Cayley from the York Hustings proposing Mr. Marshall as a Member for the County, June 19 1826, and on the Day of the Election June 27 1826. (MSS.)

39. Pamphlet "To the Inhabitants of Brompton." Reprint of a Speech made by Sir George Cayley on the Relationships of Landlords, Farmers and Farm Labourers. Scarborough. December 23 1830.

40. Pamphlet "To the Worthy Burgesses of the Borough of Scarborough" offering himself as a Candidate for Parliament. Scarborough. April 1831.

41. Speech in favour of Sir John Johnstone as Parliamentary Candidate for the County of York. May 6 1831.

42. The Speech of Sir George Cayley, Bart., delivered from the Hustings in Front of the Town Hall, Scarborough, on his nomination to serve in Parliament as one of the Representatives of that Borough, December 12 1832. Scarborough.

43. Poster. Appeal "To the Worthy and Independent Electors of Scarborough who have given or intend to give me their support." Scarborough. 1835.

44. Address delivered August 17 1835 on placing the first stone of the Chapel at Snainton. 1835.

45. Essay on the Means of Promoting Safety in Railway Carriages by Sir George Cayley. Reprinted from the *Mechanics Magazine*. 1841.

46. Letter to the *Yorkshireman* appealing for subscriptions to a Fund to Relieve Distress in the Mining and Manufacturing Districts of Yorkshire. July 1842.

47. Speech on the occasion of a Presentation of a Testimonial to the Rev. J. C. Simpson, Curate of the Parish Church of Brompton. January 1849.

48. Speech in the House of Commons on Presentation to Parliament of a Petition from the Householders and Inhabitants of Scarborough to be allowed to choose their own magistrates and other municipal officers. From *The Mirror of Parliament*. Undated.
References 36-48 are from a bound volume in the Central Library, Scarborough.

GENERAL REFERENCES

49. Files of the *Leeds Intelligencer* and *Leeds Mercury*, 1809-1857.

50. Annual Reports of the Yorkshire Philosophical Society. 1821-1858.

51. Annual Reports of the Scarborough Philosophical Society. 1831-1858.

53. Annual Reports of the Aeronautical Society of Great Britain. 1866-1883.

54. Some Notes on Sir George Cayley as a Pioneer of Aeronautics. J. E. Hodgson. A lecture read before the Newcomen Society and reprinted in the *Journal of the Royal Aeronautical Society*. August 1923.

55. *Cayley on Airships*. Edited by W. L. Lockwood Marsh. From papers in *Tilloch's Philosophical Magazine* 1816-17. *Journal of the Royal Aeronautical Society*. February 1925.

56. Sir George Cayley, the Founder of British Aeronautical Science. J. E. Hodgson. *Journal of the Royal Aeronautical Society*. May 1936.

57. The Legards of Anlaby and Ganton. Sir J. D. Legard. 1926.

58. The British Association, 1831-1921. O. J. R. Howarth. 1922.

59. L'Aeronautique. *Bulletin l'Aerotechnique*, No. 147. 1935. A propos du Carnet de notes de Sir George Cayley. Pierre Leglise.

60. Memoir of Sir George Cayley. *The Mirror*. New series. Vol. III. 1843.

61. *The Conquest of the Air*. A. Berget. London 1909.

62. *A History of Aircraft*. F. A. Magoun and E. Hodgins. New York, 1931.

63. *The Papers of Wilbur and Orville Wright*. Edited by Marvin W. McFarland. McGraw-Hill, New York. 1953.

64. *Aerodynamics*. T. von Kármán, New York and Oxford, 1954.

APPENDIX

(Reprinted from Nicholson's Journal of Natural Philosophy, Chemistry and The Arts, Vol. xxiv 1809; Vol. xxv 1910)

On Aerial Navigation†

By SIR GEORGE CAYLEY, BART.

BROMPTON, 6TH SEPTEMBER 1809

**SIR,

I observed in your *Journal* last month, that a watchmaker at Vienna, of the name of Degen*, has succeeded in raising himself in the air by mechanical means. I waited to receive your present number, in expectation of seeing some farther account of this experiment, before I commenced transcribing the following essay upon aerial navigation, from a number of memoranda which I have made at various times upon this subject. I am induced to request your publication of this essay, because I conceive in stating the fundamental principles of this art, together with a considerable number of facts and practical observations that have arisen in the course of much attention to this subject, I may be expediting the attainment of an object that will in time be found of great importance to mankind; so much so, that a new era in society will commence from the moment that aerial navigation is familiarly realised.

It appears to me, and I am more confirmed by the success of the ingenious Mr. Degen, that nothing more is necessary, in order to bring the following principles into common practical use, than the endeavours of skilful artificers, who may vary the means of execution, till those most convenient are attained.**

Since the days of Bishop Wilkins the scheme of flying by artificial wings has been much ridiculed, and indeed the idea of attaching wings to the arms of a man is ridiculous enough, as the pectoral muscles of a bird occupy more than two-thirds of its whole muscular strength, whereas in man the muscles that could operate upon the wings thus attached would probably not exceed one-tenth of the whole mass. There is no proof that, weight for weight, a man is comparatively weaker than a bird; it is therefore probable, if he can be made to exert his whole strength advantageously upon a light surface similarly proportioned to his weight, that he would fly like a bird, **and the ascent of Mr. Degen is a sufficient proof of the truth of this statement.** The flight of a strong man by great muscular exertion, though a curious and interesting circumstance, inasmuch as it will be probably the first means of ascertaining this power and supplying the basis whereon to improve it, would be of little use. I feel perfectly confident, however, that this noble art will soon be brought home to man's general convenience, and that we shall be able to transport ourselves and families, and their goods and chattels, more securely by air than by water, and with a velocity of from 20 to 100 miles per hour. To produce this effect it is only necessary to have a first mover, which will generate more power in a given time, in proportion to its weight, than the animal system of muscles.

The consumption of coal in a Boulton and Watt's steam engine is only about 5½ lbs. per hour for the power of one horse. The heat produced by the combustion of this portion of inflammable matter is the sole cause of the power generated, but it is applied through the intervention of a weight of water expanded into steam, and a still greater weight of water to condense it again. The engine itself likewise must be massive enough to resist the whole external pressure of the atmosphere, and therefore is not applicable to the purpose proposed. Steam engines have lately been made to operate by expansion only, and these might be so constructed as to be light enough for this purpose, provided the usual plan of a large boiler be given up and the principle of injecting a proper charge of water into a mass of tubes, forming the cavity for the fire, be adopted in lieu of it. The strength of vessels to resist internal pressure being inversely as their diameters, very slight metallic tubes would be abundantly strong, whereas a large boiler must be of great substance to resist a strong pressure. The following estimate will show the probable weight of such an engine with its change for one hour:—

	lb.
The engine itself	90 to 100
Weight of inflamed cinders in a cavity presenting about 4 ft. surface of tube	25
Supply of coal for one hour	6
Water for ditto, allowing steam of one atmosphere to be 1/1,800 the specific gravity of water	32
	163

I do not propose this statement in any other light than as a rude approximation to truth, for as the steam is operating under the disadvantage of atmospheric pressure it must be raised to a higher temperature than in Messrs Boulton and Watt's engine, and this will require more fuel; but if it take twice as much still the engine would be sufficiently light, for it would be exerting a force equal to raising 550 lbs. one foot high per second, which is equivalent to the labour of six men, whereas the whole weight does not much exceed that of a man.

It may seem superfluous to inquire further relative to a first mover for aerial navigation, but lightness is of so much value in this instance that it is proper to notice the probability that exists of using the expansion of air, by the sudden combustion of inflammable powders or fluids, with great advantage. The French have lately shown the great power produced by igniting inflammable powders in close vessels, and several years ago an engine was made to work in this country in a similar manner by inflammation of spirit of tar. I am not acquainted with the name of the person who invented this engine, but with some minutes with which I was favoured by Mr. William Chapman, of Newcastle, I find that 30 drops of oil of tar raised 8 cwt. to the height of 22 inches; hence one horsepower would

†The first two paragraphs were omitted in the reprint in the Annual Report for 1876, and the Aeronautical Classics 1910. Paragraphs, or words so omitted, are noted throughout this reprinting thus ** **.

*Jakob Degen (1746-1846) experimented between 1808-1812, "raising himself and his wings in the air beneath a small balloon." His wings "made of silk stretched over an oblong conical framework, supported by king-post bracing, and affording a supporting surface of 130 square feet—his endeavours were useless." J. E. Hodgson.

consume from 10 to 12 lbs. per hour, and the engine itself need not exceed 50 lbs. in weight. I am informed by Mr. Chapman that this engine was exhibited in a working state to Mr. Rennie, Mr. Cartwright, and several other gentlemen capable of appreciating its powers, but that it was given up in consequence of the expense attending its consumption, being about eight times greater than that of a steam engine of the same power. Probably a much cheaper engine of this sort might be produced by a gas-tight apparatus and by firing the inflammable air generated with a due portion of common air under a piston. Upon some of these principles it is perfectly clear that force can be obtained by a much lighter apparatus than the muscles of animals or birds, and therefore in such proportion may aerial vehicles be loaded with inactive matter. Even the expansion steam engine, doing the work of six men and only weighing equal to one, will as readily raise five men into the air as one man can elevate himself by his own exertions, but by increasing the magnitude of the engine 10, 50 or 500 men may equally be well conveyed, and convenience alone, regulated by the strength and size of materials, will point out the limit for the size of vessels in aerial navigation.

Having rendered the accomplishment of this object probable upon the general view of the subject, I shall proceed to point out the principles of the art itself. For the sake of perspicuity I shall, in the first instance, analyse the most simple action of the wing in birds, although it necessarily supposes many previous steps.

When large birds, that have a considerable extent of wing compared with their weight, have acquired their full velocity, it may frequently be observed that they extend their wings, and without waving them continue to skim for some time in a horizontal path. Fig. 1 (Plate 1) represents a bird in this act. Let *ab* be a section of the plane of both wings opposing the horizontal current of air (created by its own motion), which may be represented by the line *cd*, and is the measure of the velocity of the bird. The angle *bdc* can be increased at the will of the bird, and to preserve a perfectly horizontal path, without the wing being waved, must continually be increased in a complete ratio (useless at present to enter into) till the motion is stopped altogether; but at one given time the position of the wings may be truly represented by the angle *bdc*. Draw *de* perpendicular to the plane of the wings, produce the line *cd* as far as required, and from the point *e*, assumed at pleasure in the line *de*, let fall *ef* perpendicular to *df*; then *de* will represent the whole force of the air under the wing, which being resolved into the two forces *ef* and *fd* the former represents the force that sustains the weight of the bird, the latter the retarding force by which the velocity of the motion producing the current *cd* will be continually diminished; *ef* is always a known quantity, being equal to the weight of the bird, and hence *fd* is also known as it will always bear the same proportion to the weight of the bird, as the sine of the angle *bdc* bears to its cosine, the angles *def* and *bdc* being equal. In addition to the retarding force thus received is the direct resistance which the bulk of the bird opposes to the current. This is a matter to be entered into separately from the principles under consideration, and for the present may be wholly neglected under the supposition of its being balanced by a force precisely equal and opposite to itself.

Before it is possible to apply this basis of the principle of flying birds to the purpose of aerial navigation it will be necessary to encumber it with a few practical observations.

The whole problem is confined within these limits, *viz.*—To make a surface support a given weight by the application of power to the resistance† of air. Magnitude is the first question respecting the surface. Many experiments have been made upon the direct resistance of air by Mr. Robins, Mr. Rouse, Mr. Edgeworth, Mr. Smeaton and others. The result of Mr. Smeaton's experiments and observations was that a surface of a square foot met with a resistance of 1 pound when it travelled perpendicularly to itself through air at a velocity of 21 ft. per second. I have tried many experiments upon a large scale to ascertain this point. The instrument was similar to that used by Mr. Robins, but the surface used was larger, being an exact square foot, moving round upon an arm about 5 ft. long, and turned by weights over a pulley. The time was measured by a stop watch, and the distance travelled over in each experiment was 600 ft. I shall only give the results of many carefully-repeated experiments, which are, that a velocity of 11·538 ft. per second generated a resistance of 4 oz. and that a velocity of 17·16 ft. per second gave 8 oz. resistance. This delicate instrument would have been strained by the additional weight necessary to have tried the velocity generating a pressure of one pound per square foot; but if the resistance be taken to vary as the square of the velocity, the former will give the velocity necessary for

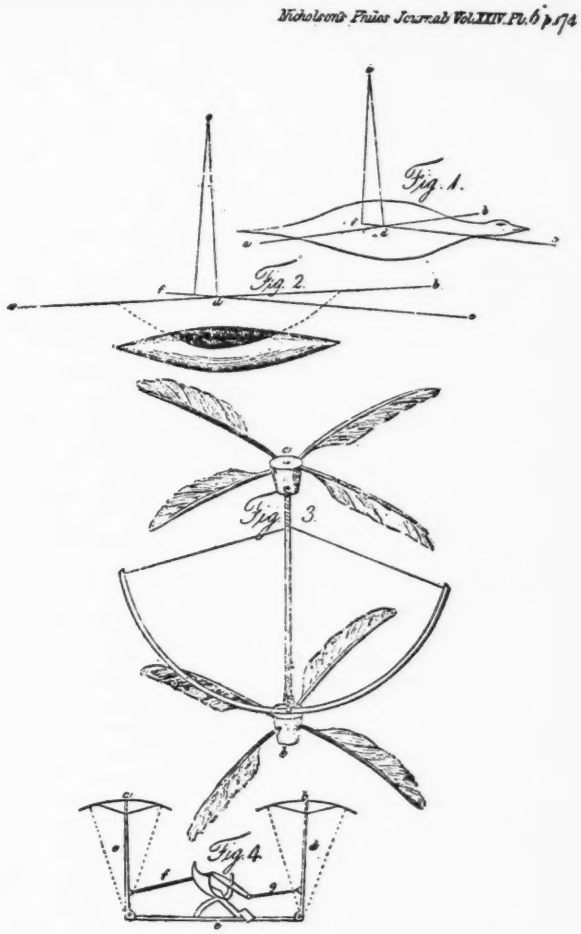


PLATE 1.

†Cayley uses the word resistance for lift or drag. Its meaning is usually clear from the text.

this purpose at 23·1 ft., the latter 24·28 ft. per second. I shall therefore take 23·6 ft. as somewhat approaching the truth.

Having ascertained this point, had our tables of angular resistance been complete, the size of the surface necessary for any given weight would easily have been determined. Theory, which gives the resistance of a surface opposed to the same current in different angles to be as the square of the sine of the angle of incidence is of no use in this case, as it appears, from the experiments of the French Academy, that in acute angles the resistance varies much more nearly in the direct ratio of the sines than as the squares of the sines of the angle of incidence. The flight of birds will prove to an attentive observer that, with a concave wing apparently parallel to the horizontal path of the bird, the same support and, of course, resistance is obtained; and hence I am inclined to suspect that under extremely acute angles, with concave surfaces, the resistance is nearly similar in them all. I conceive the operation may be of a different nature from what takes place in larger angles, and may partake more of the principle of pressure exhibited in the instrument known by the name of the hydrostatic paradox. A slender filament of the current is constantly received under the anterior edge of the surface, having created a slight vacuity immediately behind the point of separation. The fluid accumulated thus within the cavity has to make its escape at the posterior edge of the surface where it is directed considerably downward, and therefore has to overcome and displace a portion of the direct current passing with its full velocity immediately below it; hence whatever elasticity this effort requires operates upon the whole concavity of the surface, excepting a small portion of the anterior edge. This may or may not be the true theory, but it appears to me to be the most probable account of a phenomenon which the flight of birds proves to exist.

Six degrees was the most acute angle, the resistance of which was determined by the valuable experiments of the French Academy, and it gave 4/10 of the resistance which the same surface would have received from the same current when perpendicular to itself. Hence, then, a superficial foot, forming an angle of six degrees with the horizon, would, if carried forward horizontally (as a bird in the act of skimming) with a velocity of 23·6 ft. per second, receive a pressure of 4/10 of a pound perpendicular to itself; and if we allow the resistance to increase as the square of the velocity at 27·3 ft. per second, it would receive a pressure of one pound. I have weighed and measured the surface of a great many birds, but at present shall select the common rook, because its surface and weight are as nearly as possible in the ratio of a superficial foot to a pound. The flight of this bird, during any part of which they can skim at pleasure, is (from an average of many observations) about 34·5 ft. per second. The concavity of the wing may account for the greater resistance here received than the experiments upon the plane surfaces would indicate. I am convinced that the angle made use of in the crow's wing is much more acute than 6 degrees; but in the observations that will be grounded upon these data I may safely state that every foot of such curved surface, as will be used in aerial navigation, will receive a resistance of one pound perpendicular to itself when carried through the air in an angle of 6 degrees with the line of its path at a velocity of about 34 to 35 ft. per second.

Let *ab*, Fig. 2 (Plate 1) represent such a surface or sail made of thin cloth, and containing about 200 square feet (if of a square form the side will be a little more than 14 ft.), and the whole of a firm texture. Let the weight of the man and the machine be 200 lbs. Then if a current of wind blew in the direction *cd* with a velocity of 35 ft. per second, at the same time that a cord represented by *cd*, would sustain a tension of 21 lbs., the machine would be suspended in the air, or at least be within a few ounces of it (falling short of such support only in the ratio of the sine of the angle of 94 degrees compared with the radius, to balance which defect suppose a little ballast to be thrown out), for the line *de* represents a force of 200 lbs., which as before, being resolved into *df* and *fe*, the former will represent the resistance in the direction of the current, and the latter that which sustains the weight of the machine. It is perfectly indifferent whether the wind blow against the plane or the plane be driven with an equal velocity against the air. Hence if this machine were pulled along by a chord, *cd*, with a tension of about 21 lbs., at a velocity of 35 ft. per second, it would be suspended in a horizontal path; and if, in lieu of this cord, any other propelling power were generated in this direction, with a like intensity, a similar effect would be produced. If therefore the waft of surfaces advantageously moved by any force generated within the machine took place to the extent required, aerial navigation would be accomplished. As the acuteness of the angle between the plane and current increases, the propelling power required is less and less. The principle is similar to that of the inclined plane, in which, theoretically, one pound may be made to sustain all but an infinite quantity, for in this case if the magnitude of the surfaces be increased *ad infinitum*, the angle with the current may be diminished, and consequently the propelling force in the same ratio. In practice the extra resistance of the car and other parts of the machine, which consume a considerable portion of power, will regulate the limits to which this principle, which is the true basis of aerial navigation, can be carried; and the perfect ease with which some birds are suspended in long horizontal flights, without one waft of their wings, encourages the idea that a slight power only is required.

I have myself made a large machine on this principle, large enough for aerial navigation, but which I have not had an opportunity to try the effect of, excepting as to its proper balance and security. It was beautiful to see this noble white bird sail majestically from the top of a hill to any given point of the plane below it with perfect steadiness and safety, according to the set of its rudder, merely by its own weight descending in an angle of about 8 degrees with the horizon.

As it may be amusing to some of my readers to see a machine rise in the air by mechanical means, the following is a description of one of which anyone can construct at the expense of ten minutes labour:—*a* and *b*, Fig. 3 (Plate 1) are two corks, into each of which are inserted four wing feathers, from any bird, so as to be slightly inclined like the sails of a windmill, but in opposite directions in each set. A round shaft is fixed in the cork *a*, which ends in a sharp point. At the upper part of the cork *b* is fixed a whalebone bow, having a small pivot hole in its centre to receive the point of the shaft. The bow is then to be strung equally on each side to the upper portion of the shaft, and the little machine is completed. Wind up the string by turning the flyers different ways, so that the spring of the bow may unwind them with their anterior edges ascending. Then place the cork with the bow attached to it upon a table, and with the finger on the upper cork press strong enough to prevent the string from unwinding, and, taking it away suddenly, the machine will rise to the ceiling.

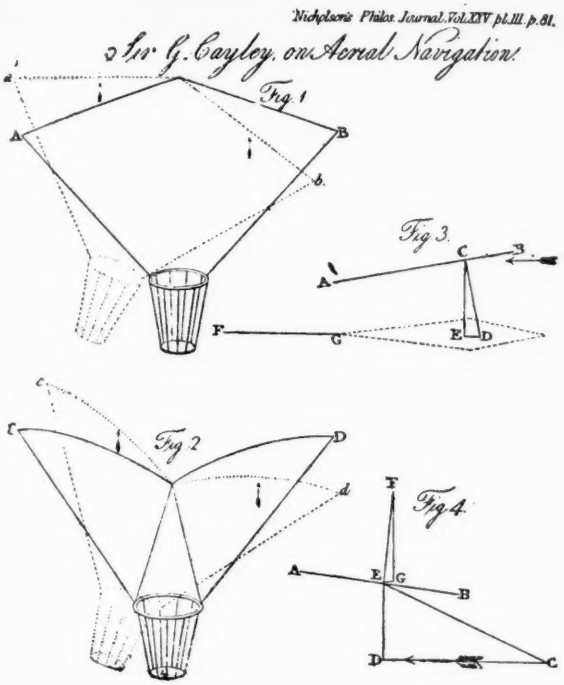


PLATE 2.

This was the first experiment I made upon this subject in the year 1796†.

If in lieu of these small feathers large planes, containing together 200 square feet, were similarly placed, or in any other more convenient position, and were turned by a man or a first mover of adequate power, a similar effect would be the consequence, and for the mere purpose of ascent this is perhaps the best apparatus; but speed is the great object of this invention, and this requires a different structure.

In lieu of applying the continued action of the inclined plane, by means of the rotative motion of flyers, the same principle may be made use of by the alternative motion of surfaces backward and forward; **and although the scanty description hitherto published of Mr. Degen's apparatus will scarcely justify any conclusion upon the subject, yet as the principle above described must be the basis of every engine for aerial navigation by mechanical means, I conceive, that the method adopted by him has been nearly as follows**:—

Let *a* and *b*, Fig. 4 (Plate 1) be two surfaces or parachutes supported upon the long shafts *c* and *d*, which are fixed to the ends of the connecting beam *e* by hinges. At *e* let there be a convenient seat for the aeronaut, and before him a cross-bar turning upon a pivot in the centre, which, being connected with the shafts of the parachute by the rods *f* and *g*, will enable him to work them alternately backwards and forwards, as represented by the dotted lines. If the upright shaft be elastic or have a hinge to give way a little, near their tops, the weight and resistance of the parachutes will incline them so as to make a small angle with the direction of their motion, and hence the machine rises. A slight heeling of the parachute towards one side, or an alteration in the position of the weight, may enable the aeronaut to steer such an apparatus tolerably well; but many better constructions may be formed for combining the requisites of speed, convenience, and steerage. **It is a great point gained, when the first experiments demonstrate the practicability of an art; and Mr. Degen, by whatever means he has effected this purpose, deserves much credit for his ingenuity.**

Having described the general principle of support in aerial navigation, I shall proceed to show how this principle must be applied so as to be steady and manageable. Several persons have ventured to descend from balloons in a parachute which exactly resembles a large umbrella, with a light car suspended by cords underneath it. **Mr. Garnerin's descent in one of these machines will be in the recollection of many; and I make the remark for the purpose of alluding to the continued oscillation, or want of steadiness[1], which is said to have endangered that bold aeronaut.** It is very remarkable that the only machines of this sort which have been constructed are nearly of the worst possible form for producing a steady descent—the purpose for which they are intended. To render this subject more familiar let us recollect that in a boat swimming upon water its stability or stiffness depends, in general terms, upon the weight and distance from the centre of the section elevated above the water by any given heel of the boat on one side; and on the bulk and its distance from the centre, which is immersed below the water on the other side, the combined endeavour of the one to fall and the other to swim produces the desired effect in a well-constructed boat. The centre of gravity of the boat being more or less below the centre of suspension is an additional cause of its stability.

Let us now examine the effect of a parachute represented by *ab* Fig. 1 (Plate 2). When it has heeled into the position represented by the dotted lines, *a* is become perpendicular to the current created by the descent, and therefore resists with its greatest power; whereas the side *b* is become more oblique, and of course its resistance is much diminished. Hence, so far as this form of the sail or plane is regarded, it operates directly in opposition to the principle of stability, for the side that is required to fall resists much more in its new position, and that which is required to rise resists much less; therefore complete inversion would be the consequence if it were not for the weight suspended so very much below the surface, which, counteracting this tendency, converts the effort into a violent oscillation.

On the contrary, let the surface be applied in the inverted position as represented at *cd*, Fig. 2 (Plate 2), and suppose it to be heeled to the same angle as before represented by the dotted lines *cd*. Here the exact inverse of the former instance takes place, for that side which is required to rise has gained resistance by its new position, and that which is required to sink has lost it; so that as much power operates to restore the equilibrium in this case as tended to destroy it in the other, the operation very much resembling what takes place in the common boat. **A very simple experiment will show the truth of this

†In a letter to R. B. Taylor, written in 1842, Cayley, describing this experiment, said the first idea he "ever had on the subject of mechanical flight was at Southgate about the year 1792" (*i.e.* four years earlier). Cayley would then be about 19 years of age.

[1]Garnerin made his first descent by parachute from a balloon in England in 1802. He was the first man to make a parachute descent, in Paris, in 1797. Garnerin, in a description of his descent, wrote, "I endeavoured to modulate my gravitation, and the oscillation which I experienced increased in proportion as I approached the breeze that blows in the middle regions."

theory. Take a circular piece of writing paper, and folding up a small portion, in the line of two radii, it will be formed into an obtuse cone. Place a small weight in the apex, and letting it fall from any height it will steadily preserve the position to the ground. Invert it, and if the weight be fixed, like the life boat, it rights itself instantly.**

This angular form, with apex downwards, is the chief basis of stability in aerial navigation; but as the sheet which is to suspend the weight attached to it in its horizontal path through the air must present a slightly concave surface in a small angle with the current, this principle can only be used in the lateral extension of the sheet, and this most effectually prevents any rolling of the machine from side to side. Hence the section of the inverted parachute, Fig. 2 (Plate 2) may equally well represent the cross section of a sheet for aerial navigation. The principle of stability in the direction of the path of the machine must be derived from a different source.

Let *ab*, Fig. 3 (Plate 2) be a longitudinal seetion of a sail, and let *c* be its centre of resistance, which experiment shows to be considerably more forward than the centre of the sail. Let *cd* be drawn perpendicular to *ab*, and let the centre of gravity of the machine be at any point in that line as at *d*; then if it be projected in a horizontal path, with velocity enough to support the weight, the machine will retain its relative position like a bird in the act of skimming, for drawing *ce* perpendicular to the horizon, and *de* parallel to it, the line *ce* will, at some particular moment, represent the supporting power and its opponent, the weight; and the line *de* will represent the retarding power and its equivalent, that portion of the projectile force expended in overcoming it; hence, these various powers being exactly balanced, there is no tendency in the machine but to proceed in its path with its remaining portion of projectile force.

The stability in this position, arising from the centre of gravity being below the point of suspension, is aided by a remarkable circumstance that experiment alone could point out. In very acute angles with the current it appears that the centre of resistance in a sail does not coincide with the centre of its surface, but is considerably in front of it. As the obliquity of the current decreases these centres approach and coincide when the current becomes perpendicular to the sail. Hence any heel of the machine backward or forward removes the centre of support behind or before the point of suspension, and operates to restore the original position by a power equal to the whole weight of the machine, acting upon a level equal in length to the distance the centre has removed.

To render the machine perfectly steady, and likewise to enable it to ascend and descend in its path, it becomes necessary to add a rudder in a similar position to the tail in the bird. Let *fg* be the section of such a surface parallel to the current and let it be capable of moving up and down upon *g* as a centre, and of being fixed in any position. The powers of the machine being previously balanced, if the least pressure be exerted by the current either upon the upper or under surface of the rudder, according to the will of the aeronaut, it will cause the machine to rise or fall in its path, so long as the propelling force is continued with sufficient energy.

From a variety of experiments upon this subject I find that when the machine is going forward, with a superabundant velocity, or that which would induce it to rise in its path, a very steady horizontal course is effected by a considerable depression of the rudder, which has the advantage of making use of this portion of sail in aiding the support of the weight. When the velocity is becoming less, as in the act of alighting, then the rudder must gradually recede from this position and even become elevated for the purpose of preventing the machine from sinking too much in front, owing to the combined effect of the want of projectile force sufficient to sustain the centre of gravity in its usual position, and of the centre of support approaching the centre of the sail.

The elevation and depression of the machine are not the only purposes for which the rudder is designed. This appendage must be furnished with a vertical sail and be capable of turning from side to side in addition to its other movements, which effects the complete steerage of the vessel.

All these principles upon which the support, steadiness, elevation, depression, and steerage of vessels for aerial navigation depend have been abundantly verified by experiments both upon a large and small scale. I made a machine having a surface of 300 square feet, which was accidently broken before there was an opportunity of trying the effect of the propelling apparatus, but its steerage and steadiness were perfectly proved, and it would sail downwards in any direction according to the set of the rudder. Its weight was 56 lbs. and it was loaded with 84 lbs. thus making a total of 140 lbs., about 2 square feet to one pound. Even in this state, when any person ran forward in it with his full speed, taking advantage of a gentle breeze in front, it would bear upward so strongly as scarcely to allow him to touch the ground, and would frequently lift him up and convey him several yards together.

The best mode of producing the propelling power is the only thing that remains yet untried towards the completion of the invention. I am preparing to resume my experiments upon this subject, and state the following observations in the hope that others may be induced to give their attention towards expediting the attainment of this art.

The act of flying is continually exhibited to our view, and the principles upon which it is effected are the same as those before stated. If an attentive observer examines the waft of a wing he will perceive that about one-third part towards the extreme point is turned obliquely backward, this being the only portion that has velocity enough to overtake the current passing so rapidly beneath it when in this unfavourable position. Hence this is the only portion that gives any propelling force.

To make this more intelligible let *ab*, Fig. 4 (Plate 2) be a section of this part of the wing. Let *cd* represent the velocity of the bird's path or the current, and *ed* that of the wing in its waft; then *ce* will represent the magnitude and direction of the compound or actual current striking the under surface of the wing. Suppose *ef* perpendicular to *ab*, to represent the whole pressure; *eg* being parallel to the horizon, will represent the propelling force, and *gf*, perpendicular to it, the supporting power. A bird is supported as effectually during the return as during the beat of its wing. This is chiefly effected by receiving the resistance of the current under that portion of the wing next the body, where its receding motion is so slow as to be of scarcely any effect. The extreme portion of the wing, owing to its velocity, receives a pressure downward and obliquely forward, which forms part of the propelling force, and at the same time by forcing the hinder part of the middle portion of the wing downward, so increases its angle with the current as to enable it still to receive nearly its usual pressure from beneath.

As the common rook has its surface and weight in the ratio of a square foot to the pound, it may be considered as a standard for calculation of this sort; and I shall therefore state, from the average of many careful observations,

the movements of that bird. Its velocity, represented by *cd*, Fig. 4 (Plate 2) is 34·5 feet per second. It moves its wing up and down once in flying over a space of 12·9 ft. Hence, as the centre of resistance of the extreme portion of the wing moves over a space of 0·75 of a foot each beat or return, its velocity is about 4 ft. per second, represented by the line *ed*. As the wing certainly overtakes the current it must be inclined from it at an angle something less than 7°, for at this angle it would scarcely be able to keep parallel with it unless the waft downward was performed with more velocity than the return, which may be, and probably is, the case, though these movements appear of equal duration.

The propelling power represented by *eg* under these circumstances cannot be equal to $\frac{1}{8}$ part of the supporting power *gf* exerted upon this portion of the wing, yet this, together with the aid from the return stroke, has to overcome all the retarding power of the surface and the direct resistance occasioned by the bulk of the bird.

It has been before suggested, and I believe upon good grounds, that very acute angles vary little in the degree of resistance they make under a similar velocity of current. Hence it is probable that this propelling part of the wing receives little more than its common proportion of resistance during the waft downward. If it be taken at one third of the whole surface, and one eighth of this be allowed as the propelling power, it will only amount to 1/24 of the weight of the bird, and even this is exerted only half the duration of flight. The power gained in the return of the wing must be added to render this statement correct, and it is difficult to estimate this; yet the following statement proves that a greater degree of propelling force is obtained upon the whole than the foregoing observations will justify.

Suppose the largest circle that can be described in the breast of a crow be 12 inches in area; such a surface moving at a velocity of 34·5 ft. per second would meet a resistance of 0·216 of a lb., which, reduced by the proportion of the resistance of a sphere to its great circle (given by Mr. Robins as 1 to 2·27) leaves a resistance of 0·095 of a lb. had the breast been hemispherical. It is probable, however, that the curve made use of by Nature to avoid resistance being so exquisitely adapted to its purpose will reduce this quantity to one half less than the resistance of the sphere, which would ultimately leave 0·0475 of a lb. as somewhat approaching the true resistance. Unless, therefore, the return of the wing gives a greater degree of propelling force than the beat, which is improbable, no such resistance of the body could be sustained. Hence, though the eye cannot perceive any distinction between the velocities of the beat and return of the wing, it probably exists, and experiment alone can determine the proper ratio between them.

From these observations we may, however, be justified in the remark that the act of flying requires less exertion than from the appearance is supposed.

Not having sufficient data to ascertain the exact degree of propelling power exerted by birds in the act of flying, it is uncertain what degree of energy may be required in this respect for vessels for aerial navigation; yet when we consider the many hundreds of miles of continued flight exerted by birds of passage, the idea of its being only a small effort is greatly corroborated. To apply the power of the first mover to the greatest advantage in producing this effect is a very material point. The mode universally adopted by Nature is the oblique waft of the wing. We have only to choose between the direct beat overtaking the velocity of the current, like the oar of a boat, or one applied like the wing, in some assigned degree of obliquity to it. Suppose 35 ft. per second to be the velocity of an aerial vehicle, the oar must be moved with this speed previous to its being able to receive any resistance; then if it be only required to obtain a pressure of 1/10 of a lb. upon each square foot it must exceed the velocity of the current 7·5 ft. per second. Hence its whole velocity must be 42·5 ft. per second. Should the same surface be wafted downward like a wing, with the hinder edge inclined upward in an angle of about 50° 40′ to the current, it will overtake it at a velocity of 3·5 ft. per second; and as a slight unknown angle of resistance generates a pound pressure per square foot at this velocity, probably a waft of little more than 4 ft. per second would produce this effect, one-tenth part of which would be the propelling power. The advantage in favour of this mode of application, compared with the former, is rather more than ten to one.

In combining† the general principles of aerial navigation, for the practice of the art, many mechanical difficulties present themselves which require a considerable course of skilfully-applied experiments before they can be overcome; but to a certain extent, the air has already been made navigable, and no one who has seen the steadiness with which weights, to the amount of ten stone (including four stone, the weight of the machine), hover in the air, can doubt the ultimate accomplishment of this object.

The first impediment I shall take notice of is the great power which must be exerted previous to the machine acquiring that velocity which gives support upon the principle of the inclined plane, together with the total want of all support during the return of any surface used like a wing. Many birds, and particularly water fowl, run and flap their wings for several yards before they gain support from the air. The swift (*hirundo apus. Lin.*) is not able to elevate itself from level ground. The inconvenience under consideration arises from very different causes in these two instances. The supportive surface of most swimming birds does not exceed the ratio of four-tenths of a square foot to every pound of their weight. The swift, though it scarcely weighs an ounce, measures 18 in. in extent of wing. The want of surface in the one case and the inconvenient length of wing in the other oblige these birds to aid the commencement of their flight by other expedients, yet they can both fly with great power when they have acquired this full velocity.

A second difficulty in aerial navigation arises from the great extent of lever which is constantly operating against the first mover in consequence of the distance of the centre of support in large surfaces, if applied in the manner of wings.

A third and general obstacle is the mechanical skill required to unite great extension of surface with strength and lightness of structure, at the same time having a firm and steady movement in its working parts, without exposing unnecessary obstacles to the resistance of the air. The first of these obstacles that have been enumerated operates much more powerfully against aerial navigation upon a large scale than against birds, because the small extent of their wings obliges them to employ a very rapid succession of strokes in order to acquire that velocity which will give support, and during the small interval during the return of the wing this weight is still rising, as in a leap, by the impulse of one stroke till it is again aided by another. The large surfaces that aerial navigation will probably require, though necessarily moved with the same velocity, will have a proportionately longer duration both of the beat and return of the wing, and hence a greater descent will take

†Misprinted in the Annual Report 1876, and Aeronautical Classics, No. 1, 1910, as "continuing."

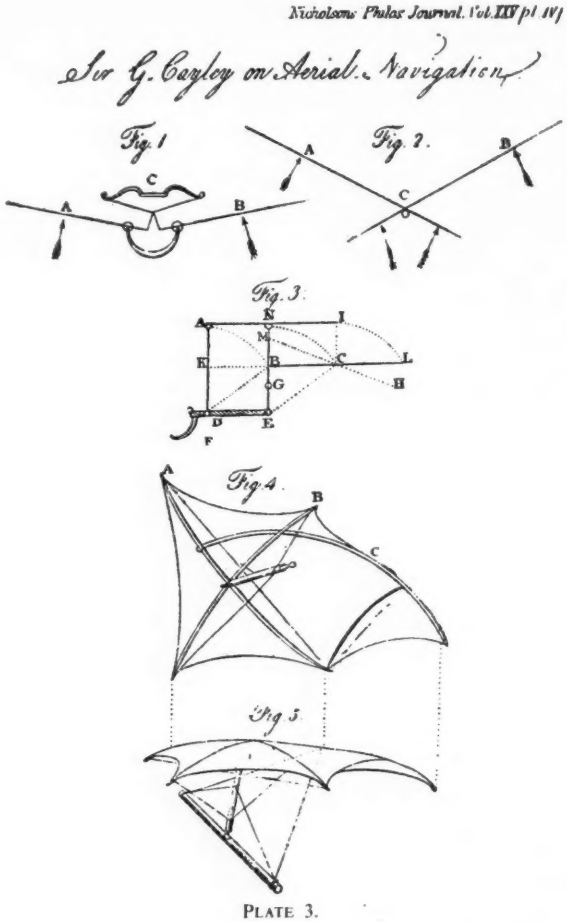


PLATE 3.

place during the latter action than can be overcome by the former.

There appear to be several ways of obviating this difficulty. There may be two surfaces, each capable of sustaining weight, and placed one above the other, having such a construction as to work up and down in opposition when they are moved, so that one is always ready to descend the moment the other ceases. These surfaces may be so made, by a valve-like structure, as to give no opposition in rising up, alternately without any up-and-down waft, as in the engine I have ascribed to Mr. Degen†; by means of a number of small wings in lieu of large ones, upon the principle of the flight of birds, with small intervals of time between each waft, and, lastly, by making use of light wheels to preserve the propelling power, both of the beat and the return of the wings, till it accumulates sufficiently to elevate the machine upon the principle of those birds which run themselves up. This action might be aided by making choice of a descending ground like the swift.

With regard to another part of the first obstacle I have mentioned, *viz.*—the absolute quantity of power demanded being so much greater at first than when full velocity has been acquired—it may be observed that, in the case of human muscular strength being made use of, a man can exert, for a few seconds, a surprising degree of force. He can run upstairs for instance with a velocity of from 6 to 8 ft. perpendicular height, per second, without any dangerous effort. Here the muscles of his legs only are in action, but, for the sake of making a moderate statement, suppose that with the activity of his arms and his body, in addition to that of his legs, he is equal to raising his weight 8 ft. per second; if in this case he weighs 11 stone, or 154 pounds, he will be exerting for the time, an energy equal to more than the ordinary force of two of Messrs Boulton and Watt's steam horses, and certainly more than twelve men can bestow upon their constant labour. If expansive first movers be made use of they may be so constructed as to be capable of doing more than their constant work, or their power may be made to accumulate for a few moments by the formation of a vacuum or the condensation of air, so that these expedients may restore at one time, in addition to the working of the engine, that which they had previously absorbed from it.

With regard to the second obstacle in the way of aerial navigation, *viz.*—the length of the leverage to which the large wing-like surfaces are exposed—it may be observed that being a constant and invariable quality, arising from the degree of support such surfaces give, estimated at their centres of resistance, it may be balanced by an elastic agent that is so placed as to oppose it.

Let *a* and *b*, Fig. 1 (Plate 3) be two wings of an aerial vehicle in the act of skimming, then half the weight of the vessel is supported from the centre of resistance of each wing, as represented by the arrows under them. If the shorter ends of these levers be connected by cords to the string of a bow *c*, of sufficient power to balance the weight of the machine at the points *a* and *b*, then the moving power will be left at full liberty to produce the waft necessary to bend up the hinder edge of the wing and gain the propelling power. A bow is not in fact an equable spring, but may be so by using a spiral fusee. I have made use of it in this place merely as the most simple mode of stating the principles I wish to exhibit. Should a counter-balancing spring of this kind be adopted in the practice of aerial navigation, a small well-polished cylinder, furnished with what may be termed a bag-piston (upon the principle made use of by Nature in preventing the return of blood to the breast, when it has been driven into the aorta by the intervention of the semilunar valves), would, by a vacuum being excited each stroke of the wing, produce the desired effect, with scarcely any loss of friction. I have made use of several of these pistons, and have no scruple in asserting that, for all blowing-engines, where friction is an evil, and being very nearly air-tight is sufficient, there is no piston at all comparable with them. The most irregular cylinder with a piston of this kind will act with surprising effect. To give an instance: a cylinder of sheet tin, 8 in. long and 3¼ in. in diameter, required 4 lbs. to force the piston down in 15 minutes, and in other trials became perfectly tight in some positions, and would proceed no farther. The friction, when the cylinder was open at both ends, did not exceed half an ounce. These elastic agents may likewise be useful in gradually stopping the momentum of large surfaces when used in any alternate motion, and in thus restoring it during their return.

Another principle that may be applied to obviate this leverage of a wing is that of using such a construction as will make the supporting power of the air counterbalance

†Both in the Annual Report for 1876 and the Aeronautical Classics reprint of 1910, the wording was "as in the engine I have described at Fig. 12." The description of Fig 12 (*i.e.* Fig. 4 (Plate 3) on a following page makes no reference to Degen. This is a shocking example of editing from an original for the purposes of a reprint. That Degen was a complete failure does not invalidate the principle of good editing.

itself. It has been before observed that only about one-third of the wing in birds is applied in producing the propelling power, the remainder, not having velocity sufficient for this purpose, is employed in giving support both in the beat and return of the wing.

Let *a* and *b*, Fig. 2 (Plate 3) be two wings continued beyond the pole or hinge upon which they turn at *c*. If the extreme parts at *a* and *b* be long and narrow they may be balanced, when in the act of skimming, by a broad extension of less length on their opposite side, this broad extension, like the lower part of the wing, will always give nearly the same support; and the propelling part of the surface will be at liberty to act unincumbered by the leverage of its supporting power. This plan may be modified many different ways, but my intention, as in the former case, is still the principle in its simplest form.

A third principle upon which the leverage of a surface may be prevented is by giving it a motion parallel to itself, either directly up and down or obliquely so. The surface *ai*, Fig. 3 (Plate 3) may be moved perpendicularly by the shaft which supports it down to the position *kc*, or if it be supported upon two shafts, with hinges at *d* and *e*, it may be moved obliquely parallel to itself into the position *bl*.

A fourth principle upon which the leverage may be greatly avoided, when only one hinge is used, is by placing it considerably below the plane of the wing, as at the point *d*, Fig. 3 (Plate3) in respect to the surface *a*. It may be observed in the heron, which is a weak bird with an extended surface, that its wings curve downward considerably from the hinge to the tip; hence the extreme portion which receives the chief part of the stroke is applied obliquely to the current it creates, and thus evades, in a similar degree, the leverage of that portion of the supportive power which is connected with the propelling power. These birds seldom carry their waft much below the level of the hinge of the wing, where this principle, so far as respects the supporting power, would vanish.

By making use of two shafts of unequal length the two last mentioned principles may be blended to any required extent. Suppose one hinge to be at *f* and the other at *g*, Fig. 3 (Plate 3) then the surface, at the extent of its beat, would be in the position of the line *hm*. If the surface *ai*, Fig. 3 (Plate 3), be supported only upon one shaft *ne*, be capable of being forced in some degree from its rectangular position in respect to the shaft, and be concave instead of flat, as here represented, then the waft may be used alternately backward and forward, according to the principles of the machine I have **ascribed to Mr. Degen.** This construction combines the principles of counterpoising the supporting power of one part of the surface by that of an opposite part when the machine is in the act of skimming, and likewise the advantages of the low hinge, with the principle of leaving little or no interval without support.

All that has hitherto appeared respecting Mr. Degen's apparatus is, that it consisted of two surfaces, which were worked by a person sitting between them. This statement communicates no real information upon the subject; for scarcely any one would attempt to fly without *two* wings; without being equally poised by placing the weight *between* them; and also without these surfaces being capable of receiving motion from his muscular action. I may be altogether mistaken in my conjecture; my only reason for ascribing the structure of mine to Mr. Degen's machine is, that, if it were properly executed upon this principle, it would be attended with success. The drawing, or rather diagram, which is given of this machine in the first part of my essay, is only for the purpose of exhibiting the principle in a form capable of being understood. The necessary bracings, &c., required in the actual execution of such a plan, would have obscured the simple nature of its action; and were therefore omitted. The plan of its movement is also simple to exhibit, in a tangible form, the possibility of effecting the intended alternate motion of the parachute. The seat is fronted lengthwise for the purpose of accommodating the mode of communicating the movement.

A fifth mode of avoiding leverage is by using the continued action of oblique horizontal flyers, or an alternate action of the same kind, with surfaces so constructed as to accommodate their position to such alternate motion, the hinge or joint being in these cases vertical. In the construction of large vessels for aerial navigation a considerable portion of fixed sail will probably be used, and no more surface will be allotted towards gaining the propelling power than what is barely necessary, with the extreme temporary exertion of the first mover, to elevate the machine and commence the flight. In this case the leverage of the fixed surface is done away.

The general difficulties of structure in aerial vehicles (arising from the extension, lightness, and strength required in them, together with great firmness in the working parts, and at the same time such an arrangement as exposes no unnecessary obstacles to the current) I cannot better explain than by describing a wing which has been constructed with a view to overcome them.

Figure 4 (Plate 3) represents the shape of the cloth, with a perspective view of the poles upon which it is stretched with perfect tightness. Upon the point where the rods *a* and *b* intersect is erected an oval shaft, embracing the two cross poles by a slender iron fork, for the purpose of preserving their strength uninjured by boring. To this shaft are braced the ends of the pole *b*, so as to give this pole any required degree of curvature. The pole *a* is strung like a common bow to the same curve as the pole *b*, and is only connected with the upright shaft by what may be called a check brace, which will allow the hinder end of this pole to heel back to a certain extent, but not the fore end. The short brace producing this effect is shown in Fig. 4 (Plate 3). Figure 5 (Plate 3) exhibits the fellow wing to that represented in Fig. 4 (Plate 3) erected upon a beam, to which it is braced so as to convert the whole length of it into a hinge. The four braces coming from the ends of this beam are shown; two of them terminate near the top of the centre of the other shaft, the others are inserted into the point *c*, Fig. 4 (Plate 3) of the tending rod. A slight bow, not more than three-eighths of an inch thick, properly curved by its string and inserted between the hinder end of the pole *a* and the curved pole *c*, completes the wing.

This fabric contained 54 square feet and weighed only 11 lbs. Although both these wings together did not compose more than half the surface necessary for the support of a man in the air, yet during their waft they lifted the weight of 9 stone. The hinder edge, as it is evident from the construction, being capable of giving way to the resistance of the air, any degree of obliquity, for the purpose of a propelling power, may be used.

I am more particular in describing this wing because it exemplifies almost all the principles that can be resorted to in the construction of surfaces for aerial navigation. Diagonal bracing is the great principle for producing strength without accumulating weight, and if performed by thin wires looped at their ends, so as to receive several laps of cordage, produces but a trifling resistance in the air and keeps tight in all weather. When bracings are well applied they make the poles to which they are attached bear endwise. The hollow form of the quill in birds is a very admirable structure for lightness combined with strength

where external bracings cannot be had, a tube being the best application of matter to resist as a lever; but the principle of bracing is so effectual that if properly applied it will abundantly make up for the clumsiness of human invention in other respects; and should we combine both these principles, and give diagonal bracing to the tubular bamboo cane, surfaces might be constructed with a greater degree of strength and lightness than any made use of in the wings of birds.

The surface of a heron's wing is in the ratio of 7 square feet to a pound. Hence, according to this proportion of wing of 54 square feet, it would weigh about 7¾ lbs. On the contrary, the wings of water fowl are so much heavier that a surface of 54 square feet, according to this structure, will weigh 18½ lbs. I have, in these instances, quoted nearly the extreme cases amongst British birds; the wing I have described may therefore be considered as nearly of the same weight in proportion to its bulk as that of most birds.

Another principle exhibited in this wing is that of the poles being couched within the cloth so as to avoid resistance. This is accomplished by the convexity of the frame and the excessive lightness of the cloth. The poles are not allowed to form the edge of the wing, excepting the extreme point of the bow, where it is very thin, and also oblique to the current. The thick part of this pole is purposely conveyed considerably within the edge. In birds a membrane covered with feathers is stretched before the thick part of the bone of the wing, in a similar manner and for the same purpose. The edge of the surface is thus reduced to a thickness of a small cord that is sewn to the cloth, and gives out loops whenever any fastening is required. The upright shaft is the only part that opposes much direct resistance to the current, and this is obviated in a great degree by a flat oval shape having its longest axis parallel to the current.

The joint or hinge of this wing acts with great firmness in consequence of its being supported by bracings to the line of its axis, and at a considerable distance from each other; in fact the bracings form the hinge.

The means of communicating motion to any surfaces must vary so much, according to the general structure of the whole machine, that I shall only observe at present that where human muscular action is employed the movement should be similar to the mode of pulling oars, from which any other required motion may be derived. The foot-board in front enables a man to exert his full force in this position. The wings I have described were wafted in this manner, and when they lifted, with a power of 9 stone, not half of the blow which a man's strength could give was exerted, in consequence of the velocity required being greater than convenient under the circumstances. Had these wings been intended for elevating the person who worked them, they should have contained from 100 to 150 square feet each, but they were constructed for the purpose of an experiment relative to the propelling power only.

Avoiding direct resistance is the next general principle that is necessary to discuss. Let it be remembered, as a maxim in the art of aerial navigation, that every pound of direct resistance that is done away with will support 30 lbs. of additional weight without any additional power. The figure of a man seems but ill calculated to pass with ease through the air, yet I hope to prove him to the full as well-made, in this respect, as the crow, which has hitherto been one standard of comparison, paradoxical as it may appear.

The principle that surfaces of similar bodies increase only as the squares of their homologous lines, while their weights, or rather solid contents, increase as the cubes of those lines, furnishes the solution. This principle is unanimously in favour of large bodies. The largest circle that can be described in a crow's breast is about 12 square inches in area. If a man exposes a direct bulk of 6 square feet the ratio of their surfaces will be as 1 to 72, but the ratio of their weight is as 1 to 110, which is 1½ to 1 in favour of the man, provided he were within a case as well-constructed for evading resistance as the body of the crow; but even supposing him to be exposed in his natural cylindric shape, in the fore-shortened posture of sitting to work his oars, he will probably receive less resistance than the crow.

It is of great importance to this art to ascertain the real solid of least resistance when the length or breadth is limited. Sir Isaac Newton's beautiful theorem upon this subject is of no practical use, as it supposes each particle of the fluid, after having struck the solid, to have free egress; making the angles of incidence and reflection equal. Particles of light seem to possess this power, and the theory will be true in that case; but in the air the action is more like an accumulation of particles, rushing up against each other in consequence of those in contact with the body being retarded.

The importance of this subject is not less than the difficulties it presents. It affects the present interests of society in its relation to the time occupied in the voyages of ships. It will still have more effect when aerial navigation, now in its cradle, is brought home to the use of man. I shall state a few crude hints upon this point, to which my subject has so unavoidably led, and on which I am so much interested, and shall be glad if in doing so I may excite the attention of those who are competent to an undertaking greatly beyond my grasp.

Perhaps some approach toward ascertaining the actual solid of least resistance may be derived from treating the subject in a manner something similar to the following:— Admit that such a solid is already attained, the length and width being necessarily taken at pleasure. Conceive the current intercepted or disturbed by the largest circle that can be drawn within the given spindle, to be divided into concentric tubular laminae of equal thickness. At whatever distance from this great circle the apex of the spindle commences, on all sides of this point the central lamina will be reflected in diverging pencils (or rather an expanding ring) making their angles of incidence and reflection equal. After this reflection they rush against the second lamina and displace it. The second lamina contains three times more fluid than the first; consequently each pencil in the first meets three pencils in the second, and their direction after the union will be one-fourth of the angle with respect to the axis which the first reflection created. In this direction these two laminae proceed till they themselves are reflected, when they (considered as one lamina of large dimensions) rush against the third and fourth, which together contain three times the fluid in the two former laminae, and thus reduce the direction of the combined mass to one-fourth of the angle between the axis and the line of the second reflection. This process is constant, whatever be the angles formed between the surface of the actual solid of least resistance at these points of reflection and the direction of the currents reflected.

From this mode of reasoning, which must in some degree resemble what takes place, and which I only propose as a resemblance, it appears that the fluid keeps creeping along the curved surface of such a solid, meeting it in very acute angles. Hence, as the experiments of the French Academy show that the difference of resistance between the

direct impulse and that in an angle of six degrees, on the same surface, is only in the ratio of 10 to 4, it is probable that in the slight difference of angles that occur in this instance the resistances may be taken as equal upon every part, without any material deviation from the truth. If this reasoning be correct it will reduce the question, so far as utility is concerned, within a strictly abstract mathematical enquiry.

It has been found by experiment that the shape of the hinder part of the spindle is of as much importance as that of the front in diminishing resistance. This arises from the partial vacuity created behind the obstructing body. If there be no solid to fill up this space a deficiency of hydrostatic pressure exists within it, and is transferred to the spindle. This is seen distinctly near the rudder of a ship in full sail, where the water is much below the level of the surrounding sea. The cause here being more evident and uniform in its nature may probably be obviated with better success, inasmuch as this portion of the spindle may not differ essentially from the simple cone. I fear, however, that the whole of this subject is of so dark a nature as to be more usefully investigated by experiment than by reasoning, and in the absence of any conclusive evidence from either, the only way that presents itself is to copy Nature. **Accordingly I shall instance the spindles of the trout and woodcock which, lest the engravings should, in addition to the others, occupy too much valuable space in your Journal, must be reserved to a future opportunity.**

THE BRITISH GOLD MEDAL FOR AERONAUTICS

Founded by the Society in 1933, the British Gold Medal for Aeronautics commemorates Sir George Cayley and his first model aeroplane of 1804. It is awarded by the Society for outstanding practical achievement leading to advancement in Aeronautics and has been awarded to the following:—

1934 Captain G. de Havilland (*Fellow*)
1936 Dr. Eckener
1937 A. Gouge (*Fellow*)
1948 E. W. Hives (*Fellow*)
1949 S. Camm (*Fellow*)
1950 Major F. B. Halford (*Fellow*)
1951 A. E. Russell (*Fellow*)
1952 G. R. Edwards (*Fellow*)
1953 R. E. Bishop (*Fellow*)
1954 A. G. Elliott (*Fellow*)

Minimum Weight Design of Thin-walled Cells in Torsion

by

V. CADAMBE, A.F.R.Ae.S. and S. KRISHNAN
(National Physical Laboratory of India)

1. Introduction

The minimum weight approach to structural design was introduced by F. R. Shanley[1] with reference to narrow and wide columns and shells subjected to bending, and was later dealt with more comprehensively in a book[2] by the same author. This was further extended to structures like tapered round thin-walled columns[3] and frames[4]. In this paper expressions giving optimum sectional dimensions for long thin-walled cells of circular, semi-circular, rectangular and triangular shapes and uniform wall thickness have been derived. The design criteria used to obtain the minimum necessary conditions are (1) failure by local buckling and (2) a limit on the twisting deformation of the cells. Working curves from which the optimum sectional dimensions can be read for given torque and limiting twist have been plotted. And finally, a method of approach to the problem of combined bending and torsion has also been indicated.

Notation

τ	shear stress in thin-walled cell
τ_θ	shear stress corresponding to limiting twist
τ_{cr}	shear stress at local buckling
τ_0	allowable shear stress
T	applied torque
T_1	"reduced torque" for rectangular section
T_2, T_2'	"reduced torques" for triangular section
θ	limiting twist
θ_1	"reduced limiting twist" for rectangular section
θ_2, θ_2'	"reduced limiting twists" for triangular section
R	radius of cell
a_1, b_1	sides of rectangular section
k_r	ratio a_1/b_1
a_2, h_2	base and side of triangular section
k_Δ	ratio $a_2/(2h_2)$
t	thickness of thin-walled cell
p	perimeter of thin-walled cell
A	sectional area of thin-walled cell
K_1, K_2	coefficients in local buckling stress formulae for circular and flat panels

2. Theory

In the treatment of thin-walled cylindrical columns Shanley considers (*i*) failure as an Euler Column and (*ii*) failure by local buckling, as the two deciding criteria and derives the optimum section by equating the Euler and local buckling stresses to the actual stress in the material. For cells subjected to torsion, however, it is felt that a limit on the twisting deformation is often a deciding factor as in the case of a control torque tube or the cell structure of an aircraft surface. The allowable twist, of course, will be dictated by the requirements of the particular problem. Thus the necessary equations are obtained by equating the shear stress τ caused by the applied torque to the shear stress τ_θ corresponding to the allowable twist and the shear stress τ_{cr} at local buckling.

Reference to any standard book on aircraft stress analysis will reveal that the first two stresses can be expressed by the relations

$$\tau = \frac{T}{2At}$$

and

$$\tau_\theta = \frac{2AG\theta}{p}$$

where T is the applied torque, A, p and t the sectional area, perimeter and wall thickness of the cell respectively and θ the limiting twist in radians. It can easily be shown that for a given torque and allowable shearing stress indefinite reduction in weight is possible by decreasing the thickness and suitably increasing other sectional dimensions. However, reduction in thickness below a certain limit results in local instability failure. There is thus an optimum thickness which will be small enough to make the weight a minimum and at the same time large enough to just prevent local buckling failure. The shear stresses at which local buckling takes place both in flat and circular panels are[5]

$$(\tau_{cr})_{circular} = K_1 E \left(\frac{t}{R}\right)^{3/2}$$

where R is the radius of the panel and

$$K_1 = \frac{1}{3\sqrt{2}(1-\mu^2)^{3/4}}$$

μ being the Poisson's ratio of the material.

Again

$$(\tau_{cr})_{flat} = K_2 E \left(\frac{t}{a}\right)^2$$

where a is the width of the element and

$$K_2 = \frac{\pi^2}{12(1-\mu^2)} \left\{ 5{\cdot}35 + 4\left(\frac{a}{L}\right)^2 \right\}$$

for two edges simply-supported, L representing the length of the panel. Since only long cells are discussed in this paper the term $4(a/L)^2$ is neglected.

Received 2nd November 1954.

The three stresses τ, τ_θ and τ_{cr} are equated for cells with particular types of sections and the optimum dimensions determined.

3. Circular Section

For a circular section the stress equations are

$$\frac{T}{2(\pi R^2)t} = \frac{2(\pi R^2)G\theta}{2\pi R} = K_1 E\left(\frac{t}{R}\right)^{3/2}. \qquad (1)$$

Solving for t and R

$$t = \{(2\pi)^{-5}(K_1E)^{-6}G\theta T^5\}^{1/14}$$

$$R = \{(2\pi)^{-3}(K_1E)^2(G\theta)^{-5}T^3\}^{1/14}.$$

Also $$\frac{R}{t} = = \{2\pi(K_1E)^4(G\theta)^{-3}T^{-1}\}^{1/7}.$$

The minimum possible value of R/t for the optimum section if stress is not to exceed an allowable τ_0 can be found by equating τ_{cr} to τ_0. Thus

$$\tau_{cr} = K_1 E\left(\frac{t}{R}\right)^{3/2} = \tau_0$$

from which $$\left(\frac{R}{t}\right)_{min} = \left(\frac{K_1E}{\tau_0}\right)^{2/3}.$$

For aluminium alloy using $10{\cdot}3 \times 10^6$ lb./in.^{2} for E, $3{\cdot}8 \times 10^6$ lb./in.^{2} for G and 0·3 for μ, and a shear allowable of 20,000 lb./in.^{2}

$$t = 0{\cdot}00272(\theta T^5)^{1/14}$$

$$R = 0{\cdot}0249(\theta^{-5}T^3)^{1/14}$$

$$\frac{R}{t} = 9{\cdot}13(\theta^{-3}T^{-1})^{1/7}$$

$$\left(\frac{R}{t}\right)_{min} = 25{\cdot}7.$$

The values of t and R have been computed for limiting twist varying from 0·01 to 0·1 degree per inch and external torque from 0 to 40,000 lb.in. for aluminium alloy and the results plotted in Figs. 1 and 2. Where there is no other condition controlling the radius it will be safe to read the optimum thickness and use for design the nearest standard thickness on the higher side.

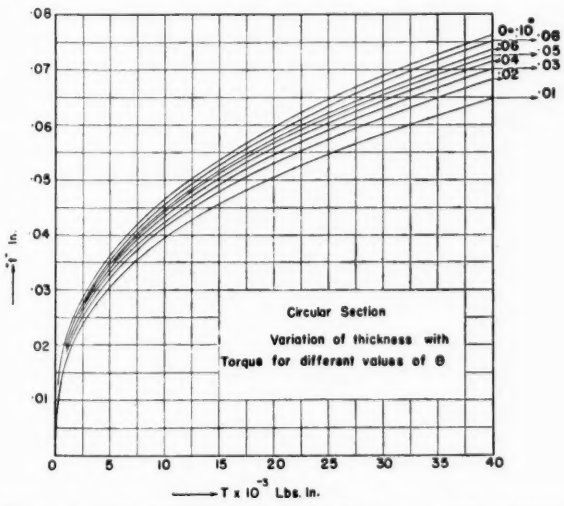


FIGURE 1. Showing the variation of thickness t with external torque T for various values of θ in degrees for a circular section.

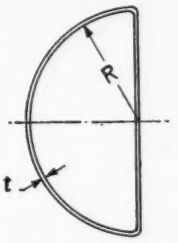


FIGURE 3. Semi-circular section.

4. Semi-Circular Section

Since this consists of a semi-circular panel covered by a flat plate of width $2R$ (Fig. 3), the optimum dimensions depend on whether the circular or flat panel will buckle first.

A comparison of the buckling stress formulae for flat and circular elements using 0·3 for μ reveals that for values of $R/t > 22{\cdot}8$ the flat element will fail first and for values of $R/t < 22{\cdot}8$ the circular element is more critical. This figure being smaller than the minimum (R/t) value for circular aluminium alloy sections, our discussion is confined to cases where $R/t > 22{\cdot}8$, or in other words to sections which fail by local instability of the flat portion.

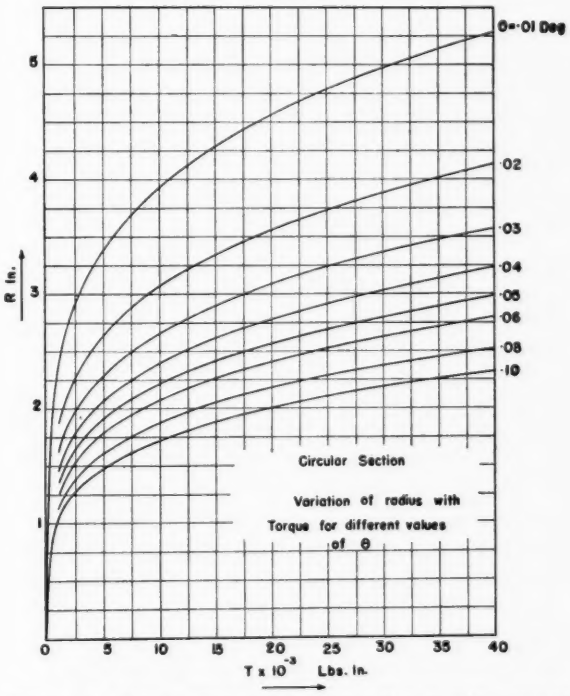


FIGURE 2. Showing the variation of radius R with external torque T for various values of θ in degrees for a circular section.

The stress equations for optimum section would then be

$$\frac{T}{2\left(\frac{\pi R^2}{2}\right)t} = \frac{2\left(\frac{\pi R^2}{2}\right)G\theta}{R(\pi+2)} = K_2 E\left(\frac{t}{2R}\right)^2. \qquad (2)$$

Solving for t and R

$$t = \left(\frac{4T}{\pi K_2 E}\right)^{1/3}$$

$$R = \{(\pi+2)(4\pi^2)^{-2/3}(G\theta)^{-1}(K_2 E T^2)^{1/3}\}^{1/3}$$

$$\left(\frac{R}{t}\right) = \left\{\frac{\pi+2}{8}(2\pi)^{-1/3}(K_2 E)^{4/3}(G\theta)^{-1}T^{-1/3}\right\}^{1/3}$$

$\left(\frac{R}{t}\right)_{\min} = \frac{1}{2}\left(\frac{K_2 E}{\tau_0}\right)^{1/2}$ is obtained by equating τ_{cr} and τ_0.

For aluminium alloy

$$t = 0{\cdot}00292\,T^{1/3}$$

$$R = 0{\cdot}0360\,\theta^{-1/3}T^{2/9}$$

$$\frac{R}{t} = 12{\cdot}2\,\theta^{-1/3}T^{-1/9}$$

$$\left(\frac{R}{t}\right)_{\min} = 25{\cdot}0.$$

It is significant that in this and the subsequent cases discussed here, the thickness is independent of the sectional dimensions or limiting twist and is dependent only on the external torque and the elastic properties of the material. In general it can be stated that where the thin-walled cell has a flat face whose local instability is critical for the cell, the thickness of wall of the optimum section is independent of the other sectional dimensions.

Figure 4 gives a plot of the wall thickness and Fig. 5 the variation of radius with external torque for values

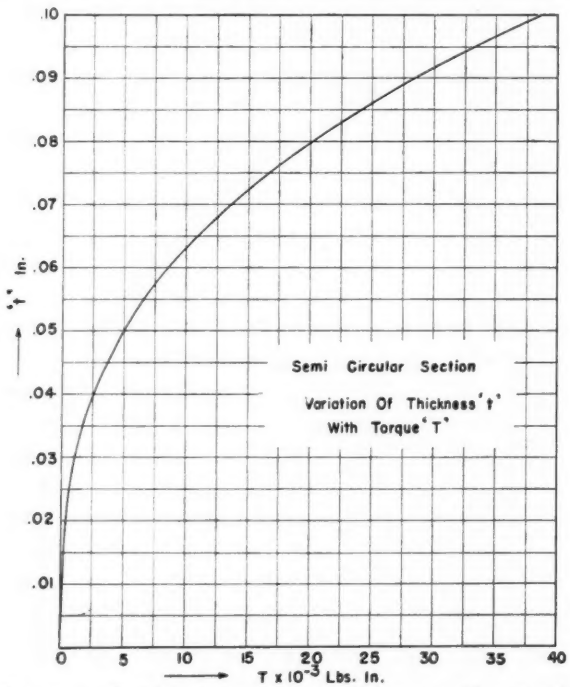


FIGURE 4. Showing the variation of thickness t with external torque T for a semi-circular section.

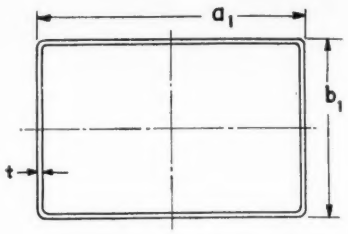


FIGURE 6. Rectangular section. $a_1/b_1 = k_r$, area $= a_1^2/k_r$.

of T ranging from 0 to 40,000 lb.in. and limiting twist from 0·01 to 0·10 degree per inch length.

5. Rectangular Section

Unlike the previous cases three conditions are required to determine fully the optimum rectangular section since the length, breadth and thickness are unknown. If a_1, and b_1 are the sides of the rectangular section where $a_1 > b_1$ (Fig. 6), and ratio $a_1/b_1 = k_r$, the stress equations will then become

$$\frac{T}{2\frac{a_1^2}{k_r}t} = \frac{2\frac{a_1^2}{k_r}G\theta}{2\left(a_1+\frac{a_1}{k_r}\right)} = K_2 E\left(\frac{t}{a_1}\right)^2. \qquad (3)$$

By introducing two new variables $T_1 = T k_r$ and $\theta_1 = \theta/1 + k_r$ which may be termed the "reduced torque" and "reduced limiting twist" respectively, the expressions obtained for optimum dimensions are made to depend only on T_1, θ_1 and the general constants. Substituting T_1 and θ_1 into (3) and solving

$$t = \left(\frac{T_1}{2K_2 E}\right)^{1/3}$$

$$a_1 = \{(2)^{-2/3}(G\theta_1)^{-1}(K_2 E)^{1/3}T_1^{2/3}\}^{1/3}$$

$$\frac{a_1}{t} = \{(2)^{1/3}(K_2 E)^{4/3}(G\theta_1)^{-1}T_1^{-1/3}\}^{1/3}$$

$\left(\frac{a_1}{t}\right)_{\min} = \left(\frac{K_2 E}{\tau_0}\right)^{1/2}$ which is twice $\left(\frac{R}{t}\right)_{\min}$ for the semi-circular section.

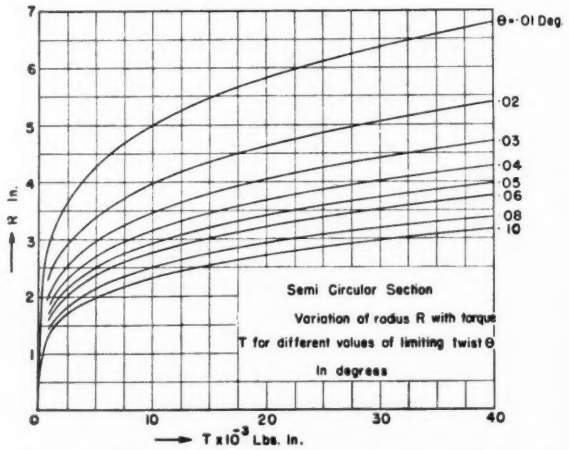


FIGURE 5. Showing the variation of radius R with external torque T for various values of θ in degrees for a semi-circular section.

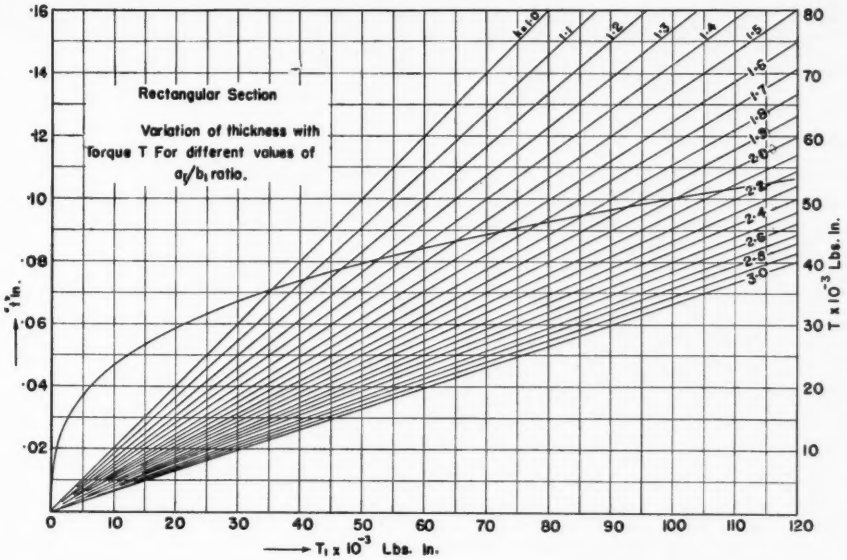


FIGURE 7. Showing the variation of thickness t with external torque T for different values of k_r for rectangular section.

a_1 and t can be computed for known values of T, θ and k_r. The square section for which $k_r=1$ will of course be the lightest for given torque and limiting twist.

In Fig. 7, t is plotted against T, together with a family of straight lines connecting T and T_1 for k_r ranging from 1 to 3. Fig. 8 gives θ against θ_1 both in degrees for the same range of k_r while Fig. 9 is a plot of a_1 with T_1 for various values of θ_1. These three curves have to be used together to read the optimum dimensions of the rectangular section.

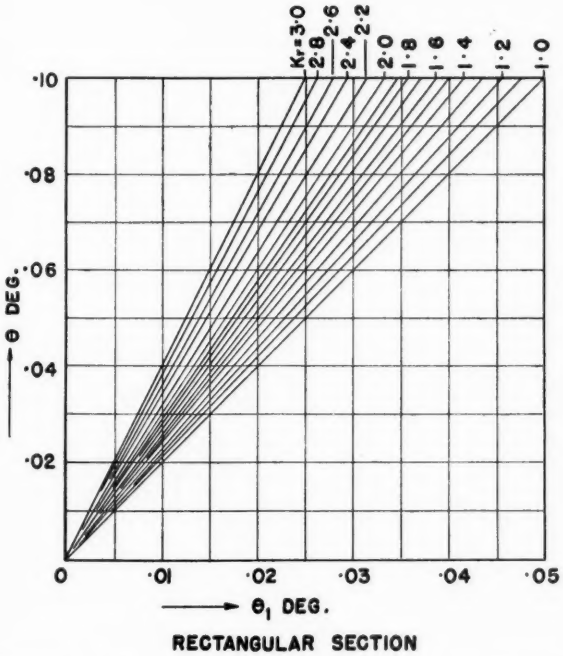


FIGURE 8. Showing the variation of θ_1 with θ for different values of k_r for rectangular section.

6. Triangular Section

Confining attention to only symmetrical triangular sections as shown in Fig. 10, it is found that two separate sets of equations have to be formed, one for cells with vertex angle $A \leqslant 60°$ and the other for angle $A \geqslant 60°$. It is always the widest element which is critical for local buckling and the conditions will differ according as

$$h_2 \gtrless a_2.$$

Let $$\frac{a_2}{2h_2} = k_\Delta .$$

In the first case, $k_\Delta > 0{\cdot}5$, the local buckling stress is $K_2 E\left(\frac{t}{a_2/(2k_\Delta)}\right)^2$ and the stress equations are

$$\frac{T}{2\left[\frac{a_2^2}{4k_\Delta}(1-k_\Delta{}^2)^{1/2}\right]t} = \frac{2\left[\frac{a_2^2}{4k_\Delta}(1-k_\Delta{}^2)^{1/2}\right]G\theta}{\left(a_2+\frac{a_2}{k_\Delta}\right)}$$

$$= K_2 E\left(\frac{t}{a_2/(2k_\Delta)}\right)^2 . \qquad (4)$$

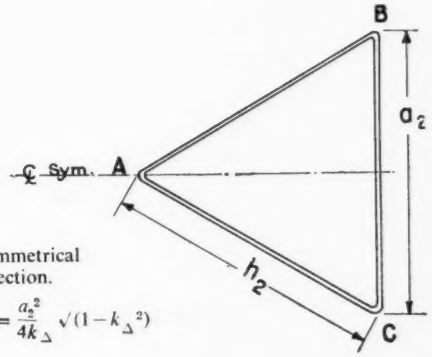


FIGURE 10. Symmetrical triangular section.

$\frac{a_2}{2h_2} = k_\Delta$, area $= \frac{a_2^2}{4k_\Delta}\sqrt{(1-k_\Delta{}^2)}$

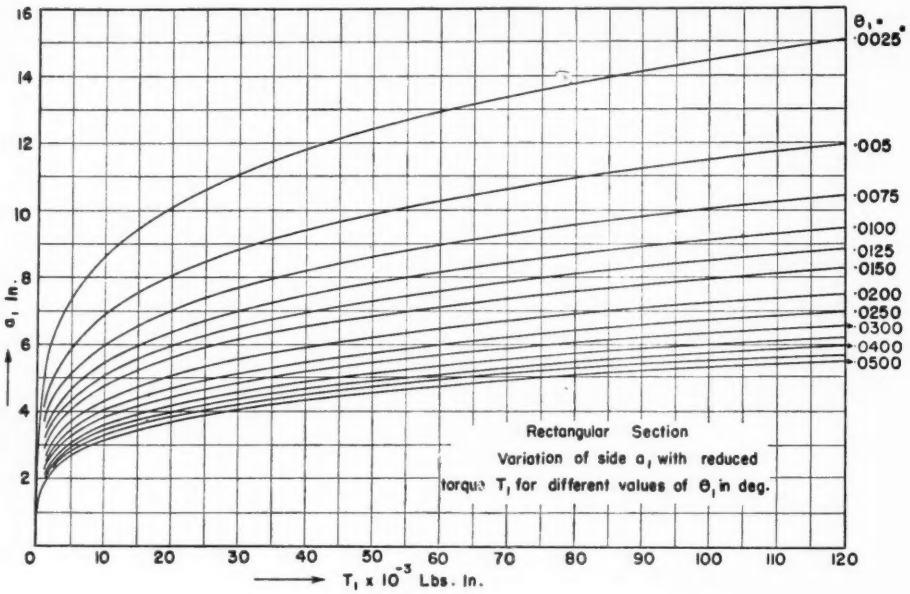


FIGURE 9. Showing the variation of side a_1 with reduced torque T_1 for different values of θ_1 in degrees, for rectangular section.

Two new variables T_2 and θ_2 are introduced as in the case of rectangular sections such that

$$T_2 = T\frac{1}{2k_\Delta(1-k_\Delta^2)^{1/2}} \quad \text{and} \quad \theta_2 = \theta\frac{(1-k_\Delta^2)^{1/2}}{8k_\Delta^2(1+k_\Delta)}.$$

Solving equations (4)

$$t = \left(\frac{T_2}{K_2E}\right)^{1/3}$$

$$a_2 = \{(K_2E)^{1/3}(G\theta_2)^{-1}(T_2)^{2/3}\}^{1/3}$$

and

$$\frac{a_2}{t} = \{(K_2E)^{4/3}(G\theta_2)^{-1}(T_2)^{1/3}\}^{1/3}.$$

In the second case where $h_2 \leqslant a_2$ or $k_\Delta \geqslant 0{\cdot}5$, the critical buckling stress becomes $K_2E(t/a_2)^2$ and the stress equations differ accordingly. They are

$$\frac{T}{2\left[\frac{a_2^2}{4k_\Delta}(1-k_\Delta^2)^{1/2}\right]t} = \frac{2\left[\frac{a_2^2}{4k_\Delta}(1-k_\Delta^2)^{1/2}\right]G\theta}{a_2+a_2/k_\Delta}$$

$$= K_2E\left(\frac{t}{a_2}\right)^2. \quad (5)$$

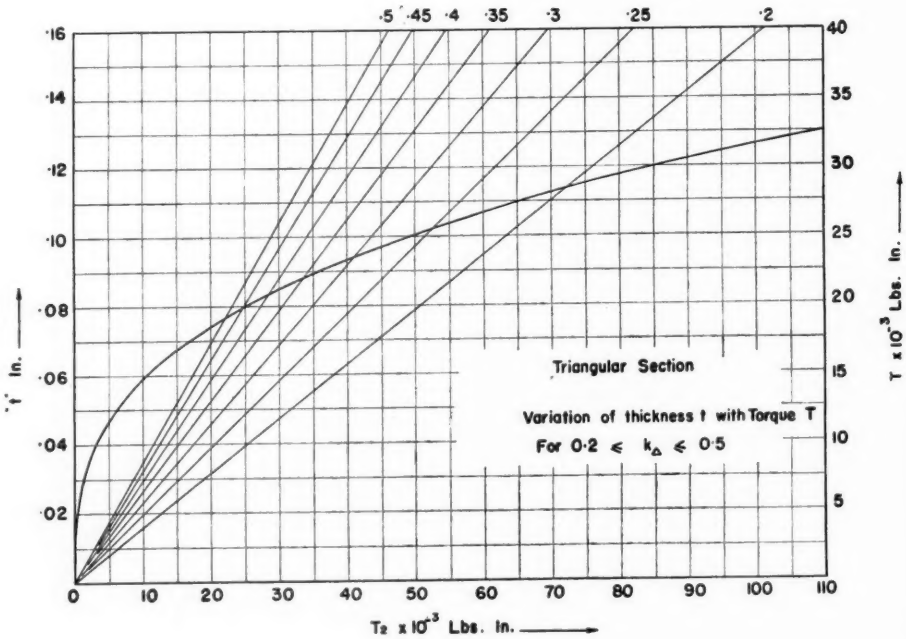


FIGURE 11. Showing the variation of thickness t with external torque T for $0{\cdot}2 \leqslant k_\Delta \leqslant 0{\cdot}5$ for triangular section.

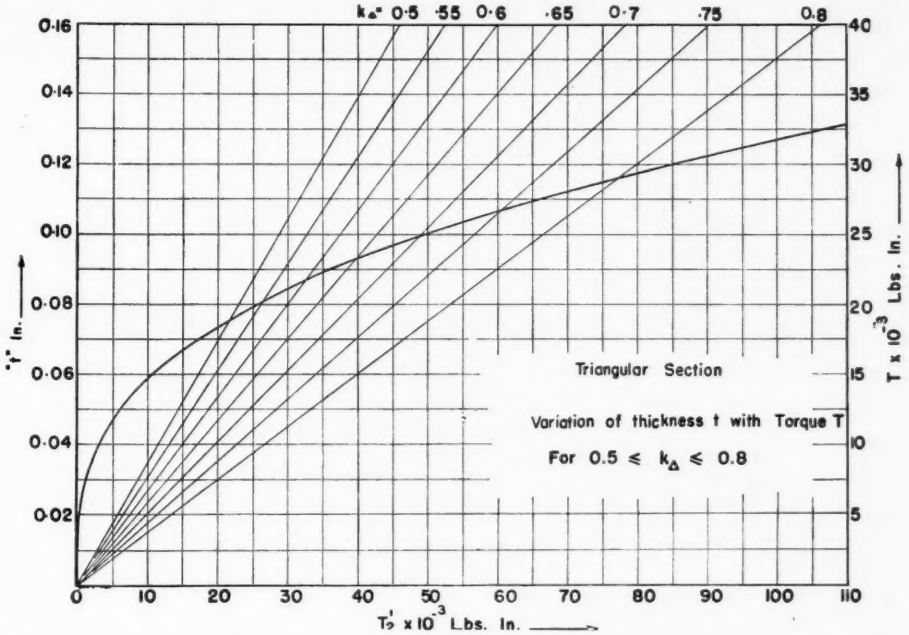


FIGURE 12. Showing the variation of thickness t with external torque T for $0{\cdot}5 \leqslant k_\Delta \leqslant 0{\cdot}8$ for triangular section.

Solutions exactly similar to those of (4) are obtained for (5) if, instead of T_2 and θ_2, we substitute

$$T_2' = T\frac{2k_\Delta}{(1-k_\Delta^2)^{1/2}}$$

and

$$\theta_2' = \theta\frac{(1-k_\Delta^2)^{1/2}}{2(1+k_\Delta)}$$

Minimum values of a_2/t can be easily computed in either case. Optimum thickness of wall for a given torque can be read from Fig. 11 for the range $0{\cdot}2 \leqslant k_\Delta \leqslant 0{\cdot}5$ and from Fig. 12 for the range $0{\cdot}5 \leqslant k_\Delta \leqslant 0{\cdot}8$. Fig. 13 shows the variation of θ with θ_2 and θ_2' for values of k_Δ between 0·2 and 0·8. Optimum values of a_2 can be read from Fig. 14 where a_2 is plotted against T_2 or T_2' for different values of θ_2 or θ_2'.

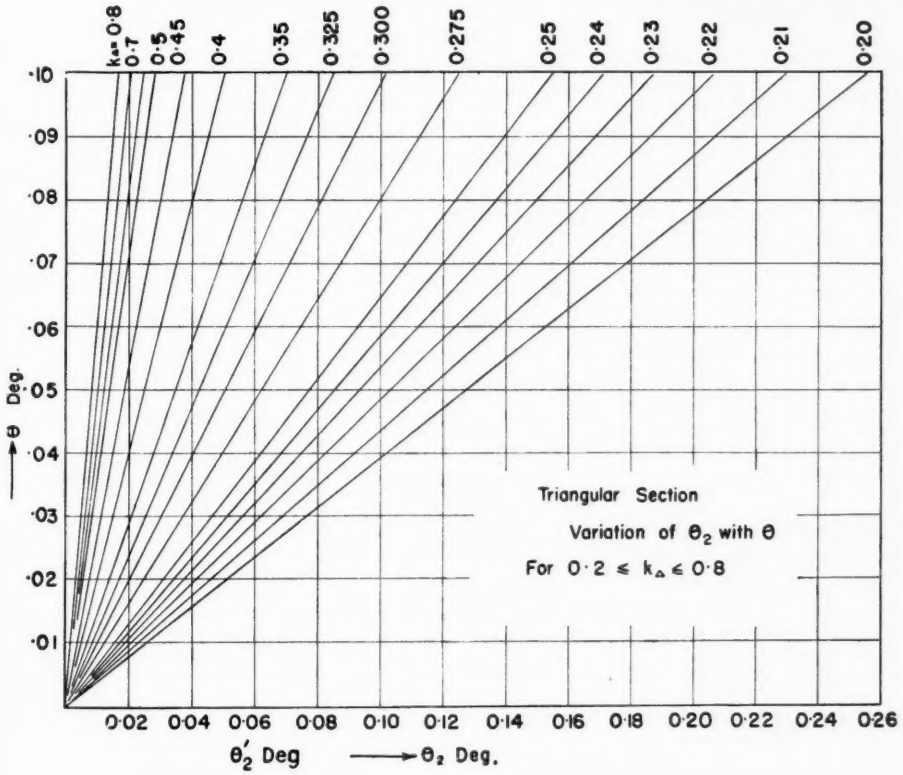


FIGURE 13. Showing the variation of θ_2 and θ_2' with θ, for $0{\cdot}2 \leqslant k_\Delta \leqslant 0{\cdot}8$ for trianglar section.

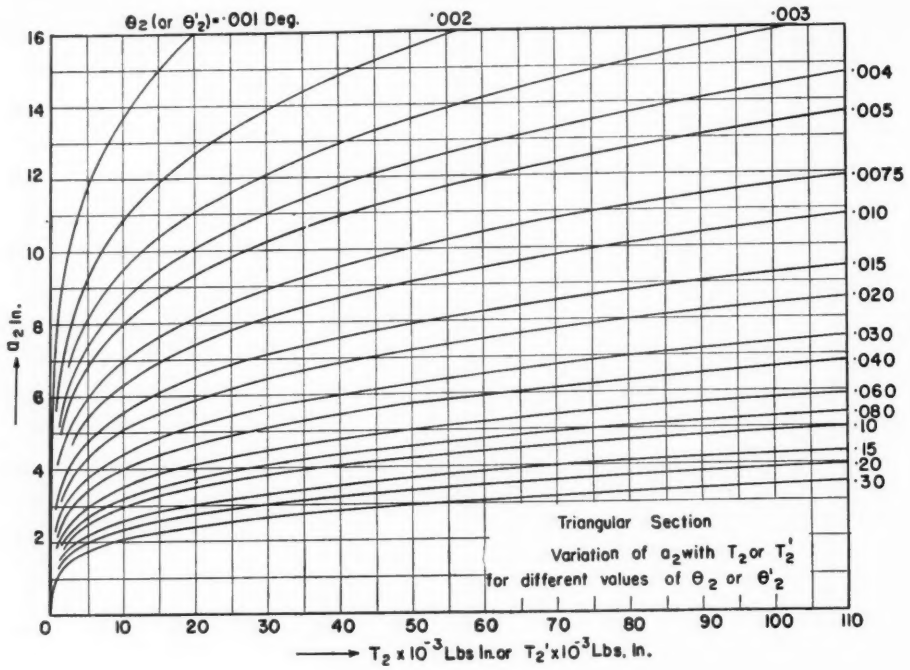


FIGURE 14. Showing the variation of base a_2 with reduced torque T_2 or T_2' for different values of θ_2 or θ_2' for triangular section.

7. Combined Bending and Torsion for Circular Sections

The problem of combined bending and torsion of thin-walled circular sections will have to be treated under two different heads, (*i*) when the bending loads are predominant and (*ii*) when the torque is predominant. In the former case one may adopt the method described in Ref. 1 except that the term for bending moment M should be replaced by the equivalent bending moment given by the well-known relation

$$M_e = \frac{1}{2}M \pm \frac{1}{2}(M^2 + T^2)^{1/2},$$

where M and T are the maximum bending moment and torque respectively.

On the other hand when torque is more predominant we have only to use the equivalent torque T_e given by $(M^2+T^2)^{1/2}$ in place of torque in the formulae derived earlier in this paper for the circular section. In some practical cases it may be necessary to determine the optimum sections for both cases and choose the one which will not fail under either condition.

8. Conclusion

The formulae derived in this paper can be used to compute the optimum sectional dimensions of a thin-walled circular, semi-circular, rectangular or triangular cell subjected to torsion on the basis of minimum weight. This does not take into account the possibility of there being other controlling factors on the sectional dimensions. However, even when there are such factors, the results can be usefully employed as a clue to the choice of the lightest sections taking these factors into account. The curves have been found to yield results within two per cent. error. By selecting the nearest standard thickness on the higher side to the optimum value read from the figure, a safe design with high strength/weight ratio can be achieved.

ACKNOWLEDGMENT

The work described in this paper is a part of the research programme of the National Physical Laboratory of India and this paper is published with the permission of the Director.

REFERENCES

1. SHANLEY, F. R. (1949). Principles of Structural Design for Minimum Weight. *Journal of the Aeronautical Sciences*, pp. 133-149, March 1949.
2. SHANLEY, F. R. (1952). *Weight Strength Analysis of Aircraft Structures*. McGraw-Hill Book Co. Inc., 1952.
3. FEIGEN MORRIS (1952). Minimum Weight of Tapered Round Thin-walled Columns. *Journal of Applied Mechanics*, pp. 375-380, Vol. 19, No. 3, Sept. 1952.
4. FOULKES, J. (1954). The Minimum Weight Design for Structural Frames. *Proceedings of the Royal Society*, pp. 482-494, May 1954.
5. TIMOSHENKO, S. (1936). *Theory of Elastic Stability*, pp. 357-362 and pp. 480-486. McGraw-Hill Book Co. Inc., 1936.

Reheat for Gas Turbines

by

J. L. EDWARDS, B.Sc., A.M.I.Mech.E., A.F.R.Ae.S.

(Chief Combustion Research Engineer, The de Havilland Engine Co. Ltd.)

The 919th Lecture to be given before the Royal Aeronautical Society was held at the Institution of Mechanical Engineers, 1 Birdcage Walk, London, S.W.1, on 21st October 1954 and was presided over by Sir Sydney Camm, C.B.E., F.R.Ae.S., President of the Society. Introducing the Lecturer, Mr. J. L. Edwards, B.Sc., A.M.I.Mech.E., A.F.R.Ae.S., Sir Sydney said the subject was one of considerable interest and importance if they were to achieve the higher Mach numbers they were told they should achieve. Mr. Edwards served a part-time apprenticeship with Yarrows of Scotstown, Glasgow, during the summers of his University course and after graduating from the University of Glasgow in 1935 he joined the experimental department of Rolls-Royce Ltd. During the war he supervised eight test hangars engaged on the testing of repaired Merlin and Griffon engines. In 1945 he joined the de Havilland Engine Co. Ltd. as Personal Assistant to the Chief Research Engineer and in 1947 was appointed to his present position of Chief Combustion Research Engineer in charge of the Gas Dynamics Laboratory.

1. Introduction

Some five years ago the author was privileged to deliver a Section Lecture to the Royal Aeronautical Society on the subject of reheat. The present paper attempts to summarise the problems which now arise and to give some idea of the progress which has been made in the intervening years.

In 1949, reheat was in its infancy in Great Britain. A certain amount of progress had been made in the United States but the information from that source was scanty and vague. Tests at the National Gas Turbine Establishment (N.G.T.E.) had given some engine data but this was in the nature of preliminary information only and was by no means complete. In fact the majority of the problems which now beset us were then completely unknown or were considered unimportant. The N.G.T.E. work was valuable, however, in that it demonstrated the practicability of reheat, although at the time the comments of many who saw this and other schemes in operation were somewhat sceptical and definitely unflattering.

In the author's original paper, therefore, little could be said about practical reheat systems because little was known. The changes in the state of a stream of gas when heat was supplied could be examined theoretically, however, and in a large measure it was the findings from such a theoretical examination that were published in 1949. A number of other techniques have appeared in print since then and, although they differ somewhat in methods of calculation, the results are much the same.

Neither the mathematics nor gas dynamics of this theory were particularly abstruse, and none of the assumptions made deviated far from practical conditions. Nonetheless, an experimental verification of the conclusions had to be obtained, and sufficient results are presented here to prove the general applicability of the theory.

Data under altitude conditions is as essential as it is difficult to obtain. There are three possible methods of obtaining this information, namely an altitude tunnel, a flying test bed or an actual fighter application. Aircraft suitable for flying test beds are few in number, generally slow and with a limited ceiling but they do have a certain value. Testing in a fighter aeroplane with only one, or perhaps two engines, is complicated and very difficult; and in both these cases the amount of useful data which is accumulated over long periods of time is lamentably small.

The position is, however, not so difficult as it would appear. The modern applications of reheat are to assist the take-off of heavily laden bombers or to force fighters up to supersonic speeds. In the former case, the system is run under ground level conditions only, and data accumulated on the test bed is directly applicable; in the latter case due to ram at high aircraft Mach numbers, the pressure level rises throughout the whole engine, and pressures and temperatures in the tailpipe at altitude may not be greatly different from those which can be simulated on the ground.

The really difficult condition occurs when the aeroplane is flying subsonically at extreme altitudes without reheat and it suddenly becomes necessary to apply full thrust boost. Gas pressures are low, extinction limits close, and the timing of the ignition, fuel admission and nozzle opening characteristics must be most carefully arranged.

Fundamentally, only three broad issues are involved in reheat. One is the flow aspect, which in the main is amenable to calculation and is the subject of the theory mentioned above; the second is combustion with its many and varied characteristics involving fuel atomisation and vaporisation, stabilisation and stability, extinction limits, and delay and reaction combustion times. Finally, mechanical design whereby a gas stream at pressures up to 80 lb./in.^{2} and temperatures up to

2,000°K. must be enclosed in a piece of pipe of negligible thickness and even less weight, and accelerated to supersonic velocities through an infinitely adjustable nozzle with a perfectly smooth profile and no base drag.

For the purpose of quantitative illustration, an arbitrary engine has been selected of mass flow 250 lb./sec., pressure ratio 7·5 and compressor and turbine efficiencies of 85 per cent. and 90 per cent. respectively. Such an engine would develop about 17,000 lb. thrust on the ground, rising to 24,000 lb. with full reheat. The fuel consumption without reheat would be 2,060 gall./hr. with an extra 4,300 gall./hr. for reheat to 2,000°K. At an aircraft Mach number of 1·5 at sea level, the reheat flow would rise to 10,000 gall./hr.

It is obvious that the normal type of engine fuel pumps will be unable to handle flows of this magnitude, and the now well known turbine-driven centrifugal pump has been developed for this purpose. Accurate control is necessary to keep the pump delivery in step with the reheat demands, and particular care must be exercised to avoid over-fuelling the reheat combustion chamber, as this would also over-fuel the engine with resultant turbine over-heating and possible damage.

2. Performance

2.1. SEA LEVEL STATIC CONDITIONS

When heat is added to a moving gas stream flowing in a parallel pipe it can be shown that the Mach number increases according to the expression:

$$\frac{M_4\sqrt{[1+\frac{1}{2}(\gamma-1)M_4^2]}}{1+\gamma M_4^2} = \frac{M_3\sqrt{[1+\frac{1}{2}(\gamma-1)M_3^2]}}{1+\gamma M_3^2}\sqrt{\frac{T_4}{T_3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and that the total pressure changes in the ratio.

$$\frac{P_3}{P_4} = \frac{1+\gamma M_4^2}{1+\gamma M_3^2}\left[\frac{1+\frac{1}{2}(\gamma-1)M_3^2}{1+\frac{1}{2}(\gamma-1)M_4^2}\right]^{\frac{\gamma}{\gamma-1}} \quad . \quad . \quad (2)$$

where subscript (3) denotes conditions before, and (4) after heat has been supplied, and

M = Mach number

$\gamma = \frac{C_p}{C_v}$ = ratio of specific heats

P = total pressure

T = total temperature.

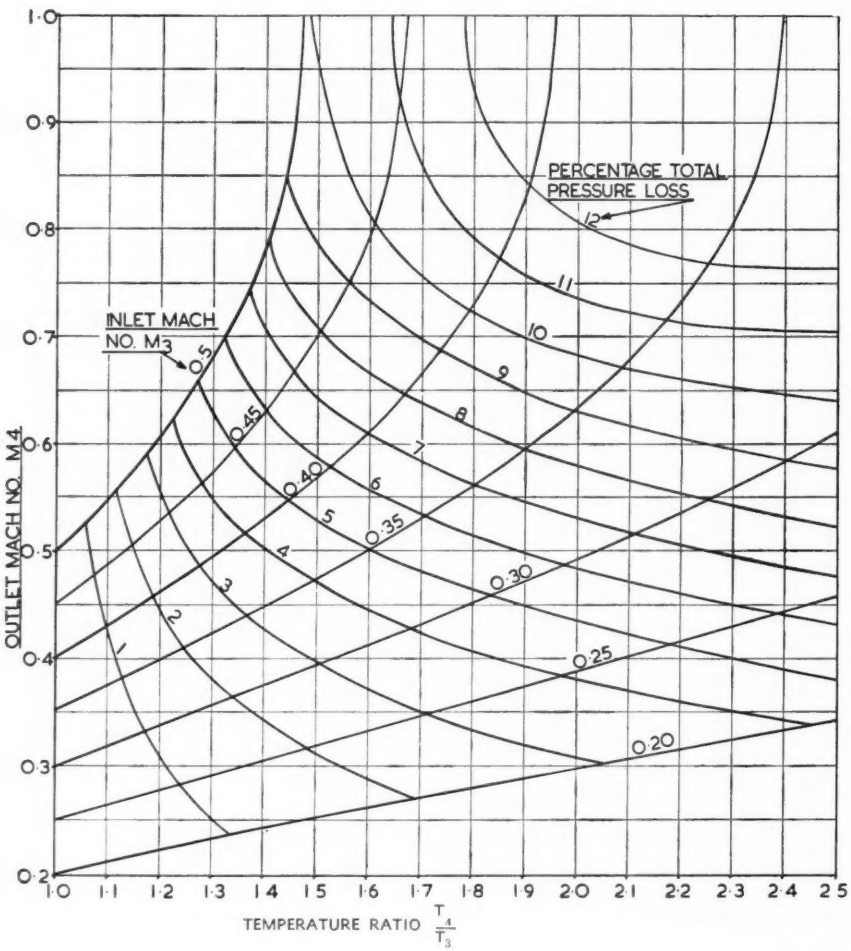


FIGURE 1. Gas flow characteristics for combustion in a parallel pipe for various inlet Mach numbers.

These equations can be most conveniently expressed graphically, as shown on Fig. 1 and they demonstrate a most important point. If the figures are transposed to show the thrust increase which may be obtained from any given system and allowance made for drag losses, then it is clear that as the temperature ratio rises, so the significance of the combustion Mach number increases. Fig. 2 shows that at temperature ratios of the order of 1·5 giving about 20 per cent. thrust increase, it makes little difference whether the tailpipe Mach number before heat is added is 0·2 or 0·3. At a temperature ratio of 2·0, however, implying a reheat temperature of the order of 2,000°K., a tailpipe Mach number of 0·2 will give a thrust increase of 42 per cent., whereas at a Mach number of 0·3 the losses so increase that only 32 per cent. will be obtained.

It is thought that this fundamental fact is not generally appreciated and there is a tendency to consider the tailpipe of the engine as a mere exhaust system, whether it is used for reheat or not. The importance of this tailpipe Mach number cannot be over-emphasised since not only does it influence the maximum available thrust boost which may be obtained, but also has a marked effect on the mechanical design and weight. Velocities and heat transfer rates rise leading to higher metal temperatures, the area of the final nozzle with reheat in operation approaches the tailpipe diameter, thus complicating the operating mechanism of the variable nozzle, stabiliser and skin friction losses increase, and the stability range narrows.

To illustrate that the fundamental theory is justified a selection of results obtained on various engines over the past few years is presented in Figs. 3 and 4. The chief parameters are the tailpipe Mach number just upstream of the stabilisers, and the cold pressure loss.

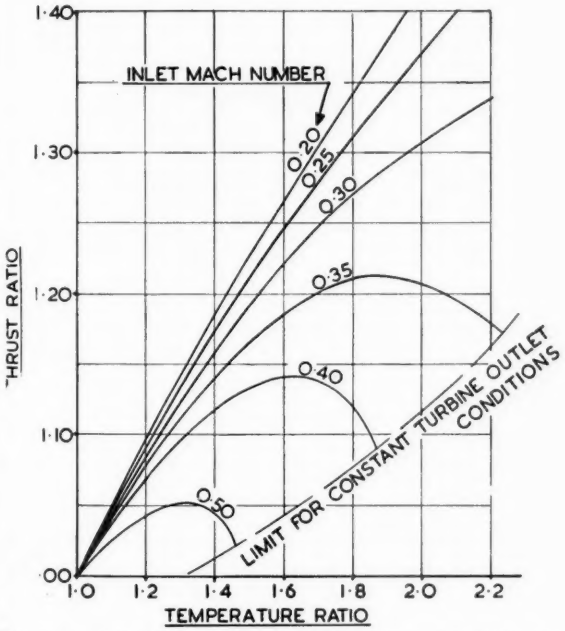


FIGURE 2. Variation of thrust ratio with temperature ratio and inlet Mach number (allowing for all losses).

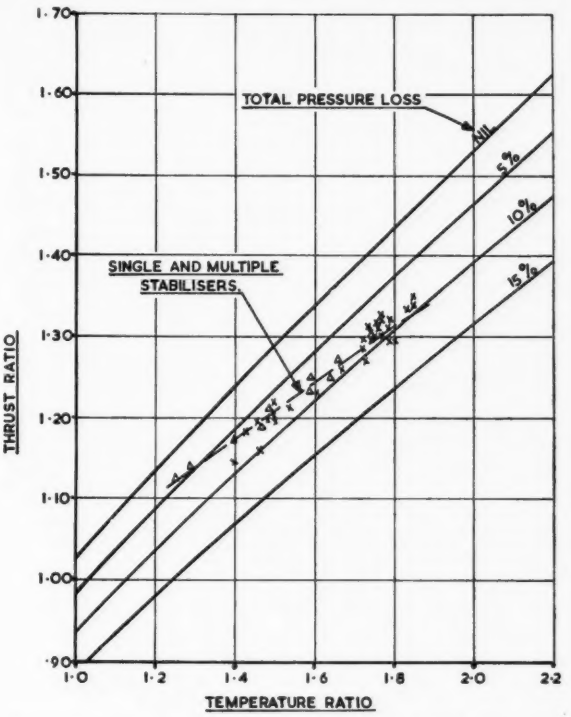


FIGURE 3. Correlation of theoretical thrust and area ratio curves with test results at a tailpipe Mach number of 0·20.

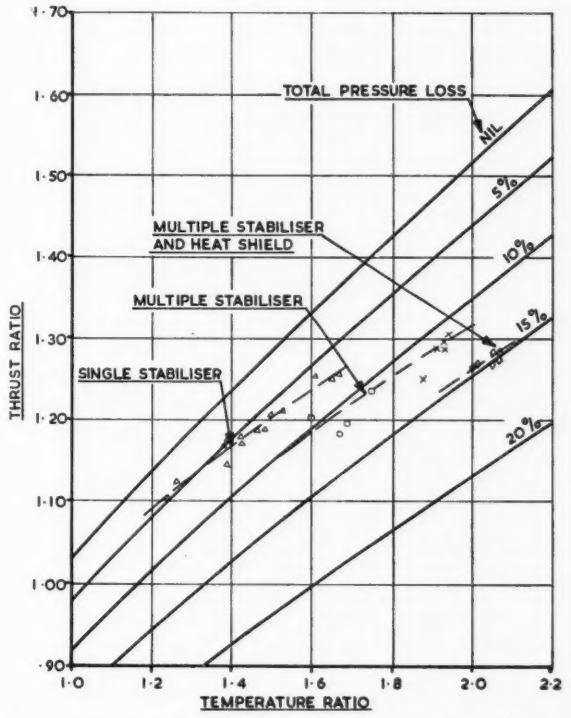


FIGURE 4. Correlation of theoretical thrust curves with test results at a tailpipe Mach number of 0·27.

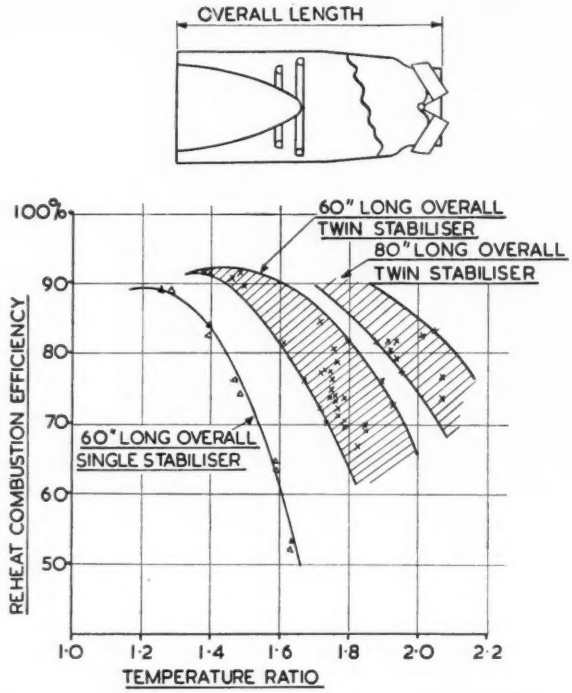


FIGURE 5. Effect of stabiliser blockage area and tailpipe length on combustion efficiency.

The points are test results taken from about nine engines, some Goblin, some Ghost, with various tailpipes ranging in length between 4 ft. and 10 ft. The agreement with the calculated curves is good, and demonstrates better than anything else how the losses increase as the temperature ratio rises.

In parallel with these thrust results, a second set of fundamental curves may be drawn relating temperature ratio to the area of the final nozzle; again, agreement between theory and practice is quite good.

Figure 5 shows a band of reheat combustion efficiencies. It is difficult to generalise the experimental evidence here, since the efficiency is a direct function of the stabiliser configuration, fuel injection arrangements and tailpipe length. None the less, the curve is interesting in that it shows the order of efficiency which may be expected from an engine of 4 : 1 compression ratio, and the general effect of blockage area and tailpipe length.

2.2. FLIGHT

Data in flight has been obtained on two single-engined aircraft, a Vampire with a specially designed long tailpipe, and a Venom where installed length was only some 12 in. above standard. The Vampire was used extensively to give performance data with thrust boosts up to 25 per cent., whereas the Venom concentrated on control problems relating to the combined operation of the variable nozzle and fuel systems.

Assessment of reheat performance in flight was exceedingly difficult despite comprehensive instrumentation. On the test bed, it is easy to measure thrusts and fuel consumptions and with this information, and a knowledge of the engine mass flow and final nozzle area, accurate thrust boosts and reheat efficiencies can be calculated. In the aeroplane, however, calculations had to be based on the propelling nozzle area ratio—for the Vampire work a fixed nozzle was used—and the turbine outlet temperature measured on four thermocouples positioned about 6 in. downstream of the turbine. Temperature measurements at this point are notoriously unreliable and although some cross checking was possible, using the calculated mass flow, observed burner ring fuel pressure and engine combustion efficiency, the results must be treated with a measure of reserve. None the less, as can be seen from Fig. 6, they do show the trend, and on the whole are probably reasonably accurate.

Determination of stability limits proved a practicable, although somewhat laborious, process. Early tests on the Vampire at 25 per cent. thrust increase were disappointing, the aeroplane climbing quite well to 8,000 ft., when violent instability set in followed by extinction of the reheat flame. At the time, it was not really known what had occurred and a series of repeat flights at reduced ratings was undertaken, starting with a smaller nozzle which had given satisfactory performances up to 50,000 ft. in a previous installation. The maximum altitude to which the aeroplane could now be flown before extinction occurred was much improved, but it was nothing like as good as before.

The only differences between the present troublesome system and its more successful predecessor lay in the size of the stabiliser and the arrangement of the fuel injector drillings. Fuel was supplied from a circular distributor ring co-axial with the stabiliser and to obtain higher boosts, all the jet sizes had been increased to provide the necessary fuel without any material increase in pressure. Some of the fuel was directed to impact on

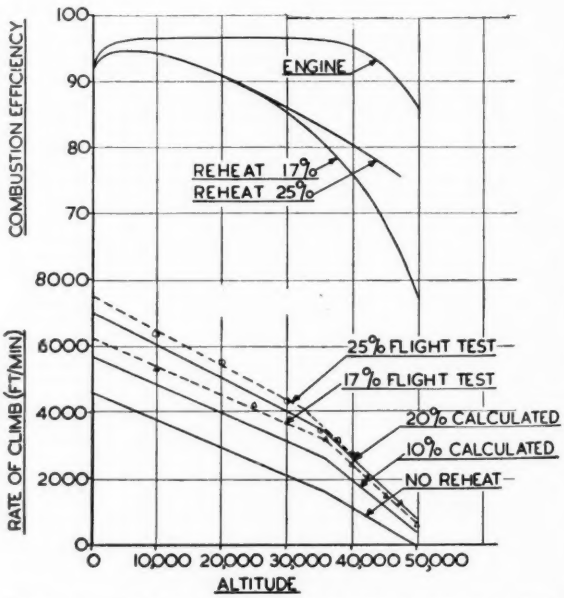


FIGURE 6. Variation of reheat combustion efficiency and rate of climb with altitude.

the back of the gutter—providing a piloting flow—and the rest was sprayed from the same fuel ring at right angles to the jet stream. Careful analysis of the results indicated that the piloting jets were supplying too much fuel and a series of flights with various propelling nozzles enabled the curve shown in Fig. 7 to be drawn. This compared the reheat burner pressures at which extinction occurred with those actually required by the 25 per cent. scheme and, as can be seen, the curves intersected at 8,000 ft. Reduction in the pilot system flow number effected an immediate cure, and flights to 44,000 ft. were then undertaken successfully.

A second, and if anything more serious, trouble then became evident. The rear cone of the aircraft overheated badly, causing blistering of the paint and deterioration of electric cables. Performance tests were therefore discontinued in favour of a prolonged programme to reduce the temperatures to an acceptable value. This was ultimately accomplished by detail improvements in the engine bay venting and the induced flow lagging, but the amount of effort which had to be expended in this direction emphasises the difficulties which can arise with reheat installations if adequate precautions are not taken to provide good thermal insulation and venting.

For work being projected, calculated rather than observed figures must be relied on. In the past it was sufficient to consider the performance of a reheat system up to aircraft speeds of six or seven hundred miles per hour, but in recent years the designers of military aircraft have begun to talk in Mach numbers up to 1·5 at sea level and 2·5 or even 3·0 at altitude. At these high Mach numbers, the bulk of the propulsive thrust comes from the reheat system and the engine is an adjunct to what is now virtually a ram-jet.

It is difficult to generalise as to what will happen to any intake-engine-reheat combination under conditions of supersonic flight. In the first place, the intake is assuming an alarming importance and its performance at off-design conditions can have far-reaching effects on the pressure-temperature relationship of the air at the compressor inlet. The engine compressor is working at low equivalent rotational speeds and its efficiency will vary by an appreciable amount. Variable intakes and compressor blades may further complicate the flow regime.

Fortunately present experience indicates that the temperature rise through the compressor is virtually constant for a given engine speed, which means that the temperature drop through the turbine also remains unchanged. Assuming constant turbine inlet temperature and efficiency, the temperature ratio across the turbine, and hence the leaving Mach number, are only slightly affected by changes in the flight conditions.

This fortunate state of affairs obviates what could have been a very difficult problem indeed, namely changes in reheat combustion Mach number during flight. Should such a state of affairs ever arise, the reheat performance is bound to be affected, and special arrangements may have to be made.

To emphasise the changes in physical conditions a number of cycle calculations have been made for the engine rating outlined in the Introduction for which

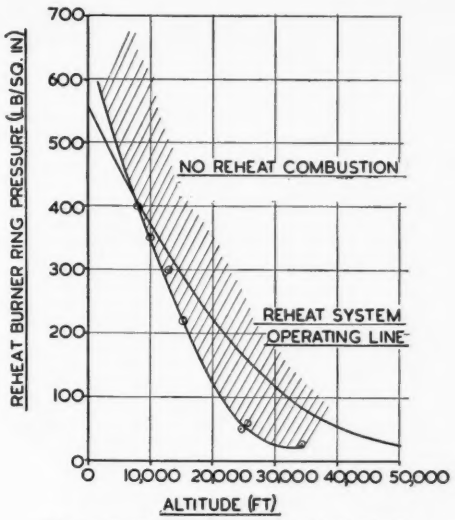


FIGURE 7. Determination of typical stability curve from flight test.

compressor characteristics and intake efficiencies have been assumed. These assumptions do preclude a general application of the results, but since the aim is to show the range of conditions under which any reheat system must work, this is not important.

Figure 8 illustrates the probable changes in tailpipe pressure; the temperature remains approximately constant. The line of demarcation between the engine with thrust augmentation and the ram-jet, where the ram pressure and turbine outlet pressure are equal, occurs at a Mach number of about 3·0 and this is probably the criterion which discriminates between these two forms of prime mover. Admittedly the ram and turbine outlet temperatures have not attained equality, but this can be achieved on the ram-jet by the admission of slightly more fuel.

At the high speed end of the flight spectrum, conditions are not too serious and the pressure and temperature at 60,000 ft., Mach number 2·0 and over, are in a relatively high pressure region where little difficulty need be anticipated from the combustion system.

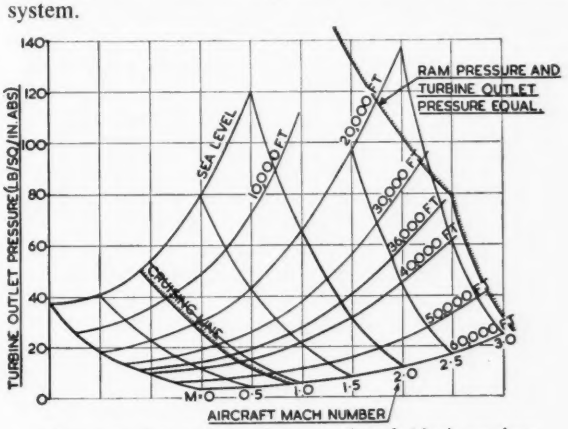


FIGURE 8. Inter-relation between aircraft Mach number, turbine outlet pressure and altitude.

NORMAL JET PIPE TEMPERATURE—1000°K. UNCHANGED WITH FLIGHT CONDITIONS. GASES FULLY EXPANDED IN CONVERGENT/DIVERGENT PROPELLING NOZZLE UNDER ALL CONDITIONS. ALTITUDE 36,000 FT. AND OVER.

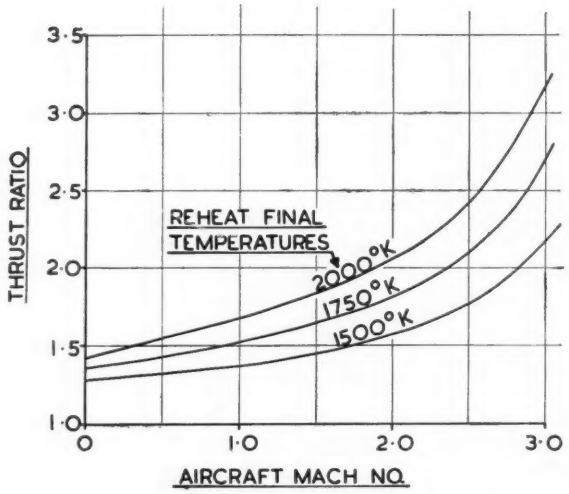


FIGURE 9. Relationship between proportionate thrust increase and aircraft Mach number.

At the lower flight speeds which will be used for cruising without reheat, this state of affairs no longer exists. Pressures have dropped to about 5·0 lb./in.² absolute, and combustion can be very difficult if not actually precarious. The fact that this is a transient state actually makes things worse, since if relatively sudden changes in air/fuel ratio are to be accommodated during the light-up and while the final nozzle is opening, the stability range must be wide.

Fortunately the position in practice is not as bad as might appear at first sight. As described at the beginning of this section, both Vampire and Venom aircraft have flown at altitudes greater than 45,000 ft. with reheat in operation, and on the Venom, successful relights have been undertaken at 40,000 ft. In these particular aircraft, conditions at 40,000 ft. to 45,000 ft. approximate to those anticipated on more modern machines at 60,000 ft., and the results obtained thus indicate that reheat light-up at extreme altitudes is perfectly feasible. Careful design of the fuel injection arrangements is important and special attention must be paid to the air/fuel ratio and fuel distribution just before light-up, and to the timing of the ignition, initial fuel injection and opening of the propelling nozzle.

The effect of intake drag becomes much more marked at high forward speeds, and the net thrust increase due to reheat rises steadily. Fig. 9 shows this change up to a flight Mach number of 3·0 from which it will be seen that the proportionate thrust increase rises from 40 per cent. at sea level static to a maximum of 215 per cent. at a Mach number of 3·0. At this point the curves steepen since the whole system tends to become a ram-jet, with the engine doing no useful work.

So far no mention has been made of fuel consumptions, for the deliberate reason that generalisation here is difficult and unreliable. So much depends on whether or not the gases are fully expanded in the propelling nozzle, what combustion efficiencies are selected for the engine and reheat systems, what allowance, if any, is made for intake losses, and so on. None the less, some attempt has been made to show the general trend, and Fig. 10 has been calculated assuming all efficiencies to be 100 per cent. and the gases in the final nozzle always fully expanded, although this is an optimum condition virtually impossible to achieve in practice.

3. General Design Requirements

In the preceding sections an attempt has been made to present a general picture of reheat as it exists today from a performance point of view, and to make some estimate of the role it will play and the conditions under which it will work in the future. Before considering the various components of the system, such as diffuser, stabiliser, fuel injection system, variable nozzle and so on, it is desirable to spend a little time in considering the design requirements and in so doing to enunciate the problems which must be understood and solved if real progress is to be made.

To attain very high forward speeds, the maximum thrust available from any given installation will almost certainly be required. This implies the highest temperatures attainable from the reheat system, theoretically obtained when the air/fuel ratio through the engine-reheat system is stoichiometric. In these circumstances the final temperature would be about 2,250° K. and every

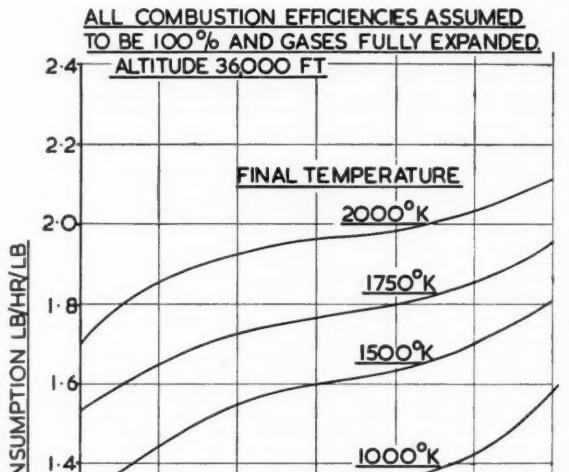


FIGURE 10. Effect of aircraft Mach number on overall specific fuel consumption.

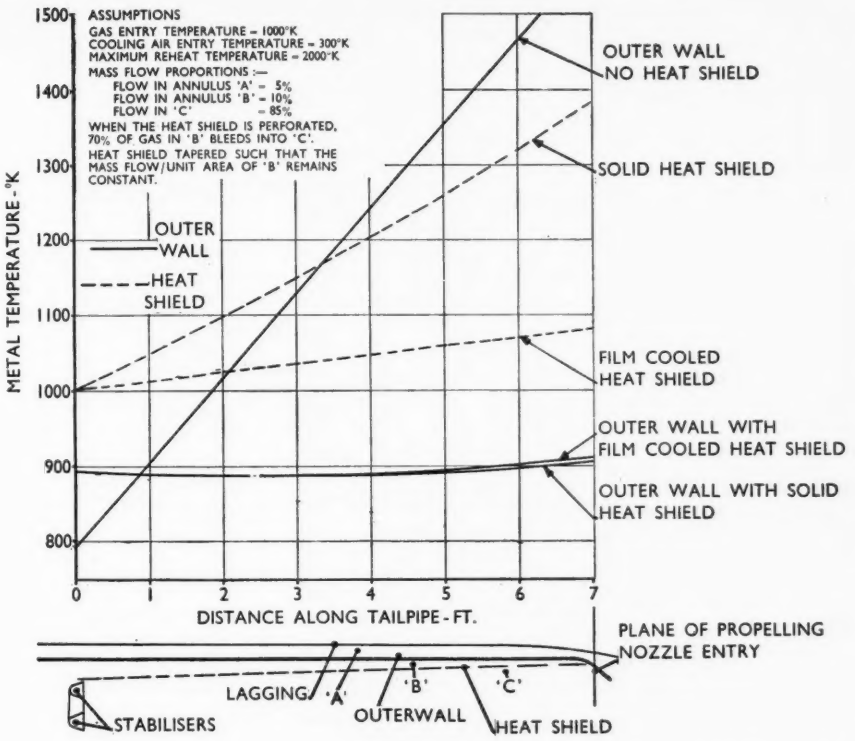


FIGURE 11. Tailpipe outer wall and heat shield temperatures.

scrap of available oxygen would have to be used. No shielding or cooling of either tailpipe, the inner cone or the final nozzle would be possible and the combustion efficiency would have to be 100 per cent.

This is obviously an optimistic state of affairs, unlikely to be realised in practice. At high temperatures it is essential to cool the tailpipe skin and the nozzle, which requires some 10 per cent. of the exhaust gases. The combustion efficiency will be between 85 per cent. and 95 per cent. depending on the length of the tailpipe which, at optimum conditions, will introduce some degree of cooling due to unburnt fuel. Allowing for these things, it is generally accepted that the maximum useful temperature is of the order of 2,000°K. corresponding to a temperature ratio over the tailpipe of about 2·0.

If even this reduced performance is to be attained, it is essential to design the tailpipe with the lowest possible Mach number in the combustion zone. There is little object in calling for a final temperature of 2,000°K. and then trying to achieve it in a gas stream initially moving at a Mach number of, say, 0·30. The losses will be so high as to render the thrust increase in going from, say, 1,750°K. to 2,000°K., insignificant; the only change will be a pronounced increase in the fuel consumption. To emphasise this point, a typical system reheating to 2,000°K. has been analysed, and Table I compares the

TABLE I

TABLE OF PRESSURE LOSSES

Reheat Mach Number	0·20	0·30
	per cent.	*per cent.*
Fundamental combustion loss	2·9	6·1
Diffuser loss	4·2	4·2
Stabiliser loss (35 per cent. blockage)	2·7	5·9
Skin friction loss (including heat shield)	0·7	2·3
Heat shield loss	0·5	1·2
Propelling nozzle loss	1·5	1·5
TOTAL LOSS	12·5	21·2

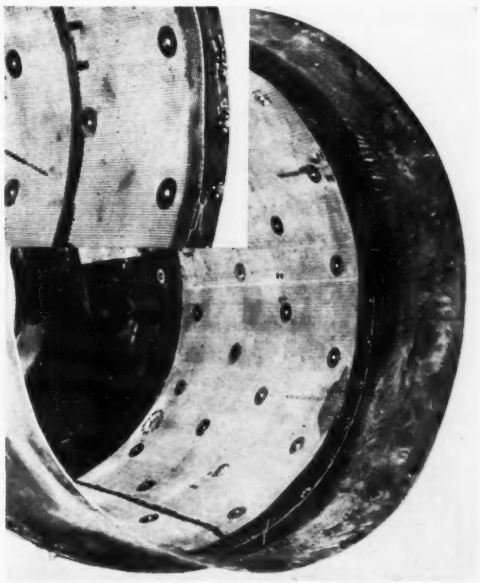


FIGURE 12. Film cooled heat shield and reheat tailpipe.

compound losses for the two cases of 0·20 Mach number and 0·30 Mach number.

The effect of a high initial Mach number can be plainly seen. It affects not only the combustion loss, but the skin friction of the tailpipe and heat shield, and the stabiliser loss. In all, the thrust gain is penalised by some 10 per cent.

If temperatures in excess of 1,750°K. are required, a heat shield is essential. A theoretical analysis of the temperatures attained by an uncooled tailpipe and one fitted with a heat shield is presented in Fig. 11, and the differences are obvious. These curves emphasise the fact that convectively cooled solid heat shields are inferior to film cooled designs and in practice it has been found that they buckle quickly, distort into the jet stream and blow out of the final nozzle. To be effective, skin cooling must be used and Fig. 12 shows an experimental pipe in which a louvred stainless steel shield is held in position by a multiplicity of bolts and distance pieces. The first run on this particular assembly lasted only about two minutes at 1,900°K. before part of the downstream section of the liner burnt away completely. This was due to bad positioning of the fuel injectors allowing a combustible fuel/air mixture to flow into the cooling gap. When this mixture emerged through the cooling flutes into the main gas stream, a flame stabilised on the edges of the metal with the inevitable result. This failure emphasises that when designing a heat shield it must be carried right up to the injectors—a rather wasteful method—or the fuel must be so controlled as to keep the cooling gas flowing between the tailpipe and the heat shield out of the combustible range.

The amount of coolant required for a heat shield must be carefully adjusted to preserve equilibrium between the pressure drops and the cooling flute areas. Because of the acceleration of the gases as they are heated, the pressure difference across the liner is highest at the downstream end. Unless due allowance is made for this, there is a risk of uneven cooling gas distribution, or the case may even arise where no gas will pass through the flutes at all—it will merely flow evenly down both sides of the liner.

Suspension in the tailpipe presents a number of problems, none of which is particularly serious, provided that it is borne in mind that there must be freedom of movement for expansion in all directions. This implies breaking the heat shield down into a number of short lengths, each fastened to the tailpipe by flexible or hinged strips, and located in each other to permit complete radial and axial movement. There is a pressure difference tending to collapse the heat shield, which, running as hot as it does, is basically very weak and all the stiffness necessary to hold it in shape must come from the supports. On the other hand, this is probably one of the occasions when too high a standard should not be set; the heat shield will work just as well in a slightly buckled state and acceptance of this fact permits a lighter construction to be used than would otherwise be possible.

The strength of the outer skin must be adequate under the worst flight conditions with full reheat. From an approximate operating line shown on Fig. 8, the maximum pressure likely to be encountered in the tailpipe is just under 80 lb./in.² or a differential pressure of 65 lb./in.² With a 0·100 in. thick, 40 in. diameter pipe, the bursting stress alone is nearly 6 tons/in.² without making any allowance for the tensile loading. This is within the 0·1 per cent. proof stress limit for

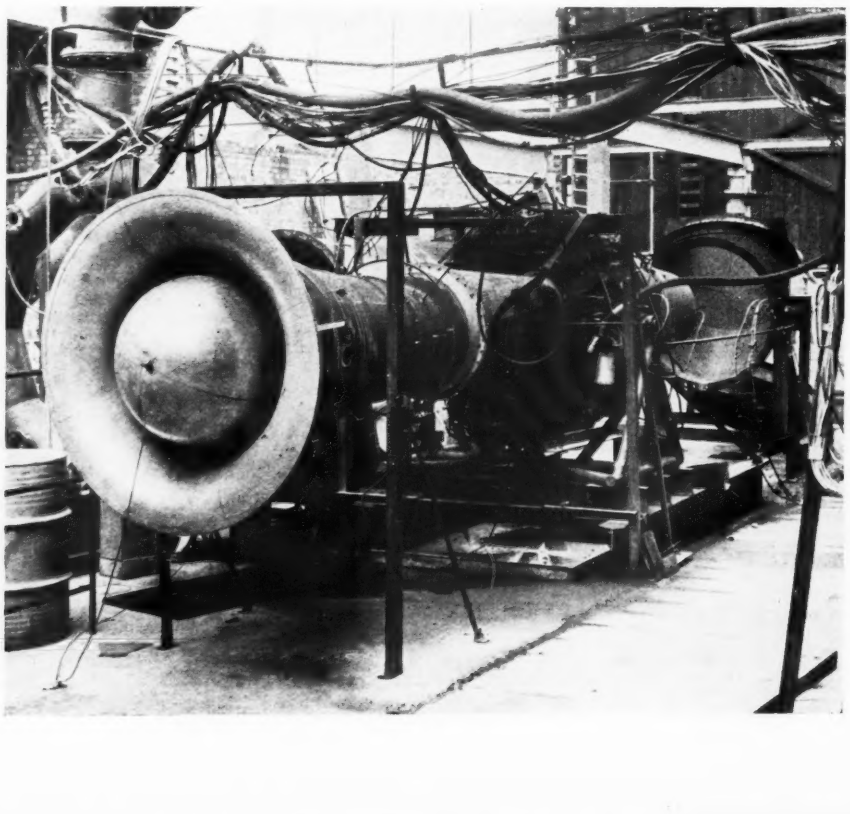


FIGURE 13. Tests on engine with complete tailpipe.

Nimonic 75 at 600°C., but if the metal temperature should rise for any reason, the safe stress could easily be exceeded. The need for a heat shield is obvious, since without it metal temperatures of the order of 1,000°C. could occur, which would be prohibitive.

The use of ceramics as a protective coating has a somewhat limited application. It is now a fairly generally accepted fact that ceramic coatings do not allow inferior materials to be used, but they do permit thinner gauges of high temperature alloys since deterioration by oxidation is delayed.

Neither gas nor flying loads on the stabilisers are high and their support is easy. None the less, care must be taken to provide freedom of movement, and it is a mistake to make the stabiliser sections too thin in the interests of weight saving. In the case of multiple stabilisers, it is often necessary to provide connecting gutters to assist ignition. The need for these does depend to some extent on the fuel system used, but if they are incorporated once again sliding joints should be used, and any rigid connections between individual rings avoided.

Fuel galleries, whether for radial spray bars or circular rings, suffer from the same movement problems as stabilisers and other parts, but since they must contain fuel at pressures of over 1,000 lb./in.^{2}, the design and manufacture of the unions and pipe connections require some care if flexibility is to be present, and leaks avoided. It is most important that the system should remain dry externally, as otherwise a serious fire risk will occur when the engine is shut down. During actual running there is little danger, but spilt fuel dripping on to a hot tailpipe without a current of air passing over it will almost certainly ignite. In the same connection it is desirable to drain all fuel pipes and galleries when shutting reheat off, thus avoiding not only the fire risk, but also any chance of the fuel cracking in the system and causing blockages.

There has been some mention of fuel boiling at high altitudes and very low fuel flows and pressures. This could upset the flow pattern in the burner system, cause uneven combustion, and probably extinction. So far, the author has not experienced this trouble, and it does not appear serious. By the time burner pressures have dropped to such a value as to permit boiling, the system will probably be troublesome for other reasons, and a duplex arrangement will be incorporated which will raise the pressures and boiling points out of the danger region.

One detail design point often overlooked is the need for streamlining of all fairings, supports, bolt heads, and so on, which are situated in the gas-fuel mixture zone. If this is not done, the protrusions or obstructions will generate eddies which in turn may well act as stabilisers. Oxidation of the part concerned is then very rapid, and complete failure inevitable.

The support fairings and inner cone assembly sometimes give trouble, due to cracking of the sheet metal. Here, once again, the secret of success seems to lie in adequate stiffness plus freedom to move. The loads on the inner bullet are somewhat higher with reheat than without, due to increased forward forces consequent on the diffusion, and stronger supports are necessary if it is not to drift forward and rub the turbine wheel. Adequate support bosses and platforms on the sheet metal walls usually obviate this trouble.

There are many other points which arise, but these are either specialised and dealt with in the next section, or fall within the sphere of general engine design. While mechanical failures have occurred from time to time on all our reheat systems, they have not proved troublesome in themselves. Usually failed sheet metal work has been the result of "screech," which can be alarmingly rapid and completely final. Since the cause rather than the effect is all-important here, details of the failures—which conformed to no particular pattern—are not considered.

4. Detail Investigations

In the preceding sections an attempt has been made to summarise the present position of reheat, showing the correlation between theory and practice which may be expected, and outlining some of the mechanical design features. From this stage development verges on research and to obtain further improvements in performance, detail studies of the individual components and processes must be made.

The following paragraphs give a broad summary of the results so far obtained. The work is far from complete, especially from the combustion aspect, and many questions must be left unanswered, some because no answer is yet known, others for security reasons. The experiments do however point the way to the future, and show how much has yet to be done.

4.1. DIFFUSERS

Much of the pressure loss in any reheat system may be debited to the annular diffusing section between the turbine outlet where the Mach number is about 0·6 and

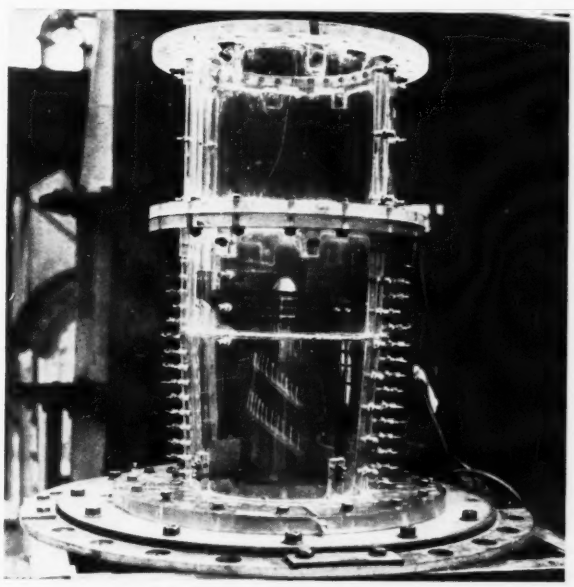


FIGURE 14. Perspex model of reheat tailpipe showing wool tufts on diffuser bullet.

the reheat combustion zone where the Mach number has dropped to between 0·2 and 0·3. Despite the importance of this part of the system, however, very little comprehensive data is available, and such design information as there is applies in the main to conical diffusers with a uniform air entry.

In practice it is unusual for the gases leaving the turbine to have no resultant swirl or for the velocity profile to be uniform. Both these effects exist to a more or less serious degree, and if an optimum diffuser is to be designed then the influence they have on performance must be known.

The ideal diffuser accepts gas flowing at a high velocity and low static pressure, and by suitable changes in area, converts conditions to those of low velocity and high static pressure. The efficiency of this process is assessed, first by the losses incurred, expressed as a percentage loss in inlet total pressure or inlet dynamic pressure; and second by the static pressure rise expressed as a ratio of ideal to actual static temperature rise or adiabatic efficiency.

There is no easy way of determining the performance of any diffuser, and it is essential to run tests on both model and full scale components. Very often the desired optimum is not possible due to considerations of length or weight, and some compromise must be made. Even when everything has been allowed for, the results may be invalidated by a bad velocity profile or swirl at the turbine outlet.

A great deal of work on diffusers has therefore been undertaken on low pressure air rigs and water rigs and full size tailpipes through which air is drawn by connecting them to the inlet of an engine have also been tested. Figs. 13 and 14 show typical set-ups for tests of this nature.

Considerable scatter in results has always been encountered, mainly due to the uneven nature of the flow at outlet, especially at large equivalent cone angles. The performance which should be attained by a reasonably good diffuser is presented in Fig. 15, but it is not recommended that equivalent cone angles in excess of 20° be used, as above this instability and excessive loss may arise. Some improvement in the figures quoted is possible by the use of splitter vanes, but these must be fitted with discretion, as the adverse effects consequent on a poor turbine outlet traverse can more than outweigh the advantages of a gentler rate of diffusion.

Careful design of the annular passage shape and rate of change of area can also effect improvements, and as a general rule it appears wise to start the diffusion gently, if possible allowing the tailpipe to increase in diameter over the turbine size, for a few inches, and then diffusing uniformly to the design Mach number. If over about 10° of whirl is present, consideration should be given to installing straightener vanes; if a big velocity profile exists, a longer diffuser will be necessary than would otherwise be required.

Better diffusion can be obtained if a certain length of parallel section is added to the annulus and some 10 per cent. greater diffuser efficiency can often be obtained. On the other hand this may be a somewhat fictitious gain since the stabilisers are usually positioned at the

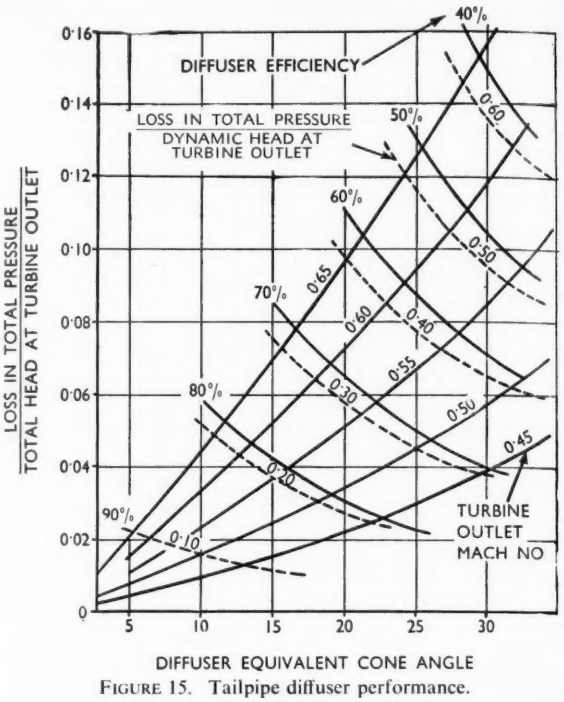


FIGURE 15. Tailpipe diffuser performance.

beginning of the parallel section, and the quality of diffusion to this particular point as represented by the curves shown herewith, is quite unaffected by any following straight section. The fact that diffusion goes on afterwards may, however, be of some benefit in that it will tend to reduce the fundamental pressure drop.

4.2. FUEL INJECTION

Superficially, fuel injection is a relatively easy matter, since atomisation of the fuel is accomplished by the high velocity gas stream in the tailpipe; in effect an air blast atomiser can be formed by merely injecting a plain jet of fuel at right angles to this gas stream.

To examine the characteristics of such a spray, a simple rig was constructed, whereby air was blown through a nozzle to atmosphere, a jet of fuel sprayed into it and the penetration and spread of the jet recorded photographically. A typical picture is shown on Fig. 16.

As the air density falls, so will the fuel flow; thus the system is to some extent self-compensating and in practice the injection distance does not seem to vary significantly. There is a possibility that this will become important at extreme altitudes and low aircraft speeds, however, and further investigation is essential.

Using a somewhat different photographic technique to that adopted for Fig. 16, the striations in the spray can be seen more clearly and from these it is possible to determine the flow lines of the droplets as they peel off the main jet. Careful analysis of these lines allows computation of the mean droplet size and fuel distribution in the spray, and it can be shown that the biggest droplets are about eight microns in diameter. This agrees with theoretical work, whereby, equating the stagnation pressure on the upstream side of the drop

with the surface tension around it, it can be shown that ten microns is about the maximum size of droplet which can exist in gas streams of the velocity under consideration.

Before any liquid fuel can be burned it must be vaporised. This vaporisation takes time, and injection too close to the gutters will cause a slowing down of the early stages of the combustion process. It is thus advisable to position injectors a short distance upstream. The time for a 10 micron droplet to vaporise is approximately half a millisecond, equivalent in a gas stream travelling at 600 ft./sec. to a distance of some 4 in. Experimental work tends to show that a rather greater distance is beneficial, but it is thought that this is due to an improvement in the mixing rather than to better vaporisation.

A great deal of experimental and theoretical work has yet to be done before the spray jet technique of fuel injection is thoroughly understood, but in the meantime, a number of empirical relationships have been evolved which allow an approximate spray pattern to be plotted for any given gas stream condition.

The arrangement, size and number of fuel jets is decided by other considerations. In any particular application of reheat, a design point is usually set which dictates the final nozzle gas temperature. While this is a useful datum, it is not always a good one, since the thrust boost obtained on any given installation is a function of the pressure losses as well as the temperature rise. From a combustion point of view, however, the reheat temperature rise is the significant variable, and it makes little difference whether or not pressure loss is allowed for. The fuel/air ratio ideally necessary to achieve a given temperature rise is easily determined from gas tables, and this in turn gives an ideal fuel flow which is almost directly proportional to the air mass flow at any given flight condition. In practice, however, all the fuel injected is not burnt, and the combustion efficiency must be allowed for. Though this is high under sea level conditions, it may fall off appreciably with altitude.

Returning to our hypothetical engine, a reheat final temperature of 1,750°K. would be achieved on the test bed with an overall fuel/air ratio of 0·0385, of which the engine fuel/air ratio would be 0·0179. These fuel/air ratios increase to 0·0428 and 0·0182 if allowance is made for 98 per cent. engine combustion efficiency and 85 per cent. reheat efficiency. In terms of fuel flow, 2,050 gall./hr. go to the engine and 2,760 gall./hr. to the reheat system.

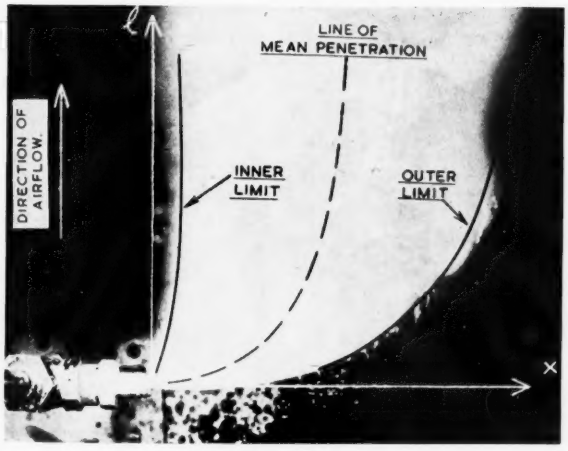


FIGURE 16. Spray penetration from a plain hole into a moving gas stream.

The minimum fuel flow likely to be encountered should now be determined, since there must be a reasonable fuel pressure under the most adverse flight conditions. These occur during light-up at extreme altitude prior to acceleration to maximum speed after patrol work under cruising conditions—probably subsonic. Here the pressure in the tailpipe is low, the mass flow is at a minimum and possibly the temperature is also down due to premature opening of the propelling nozzle. Once again quoting figures, the engine which is being used as an example, would have an air mass flow of about 35 lb./sec. at 60,000 ft., Mach No. 0·9. It would require a reheat fuel flow of only 470 gall./hr. to achieve a final temperature of 1,750°K., assuming a combustion efficiency under these conditions of 70 per cent.; a fuel flow range of nearly 6 : 1 or a fuel pressure range assuming a simplex system of 36 : 1.

It has been found from experience that fuel pressures as low as 10 lb./in.² will give effective, if not efficient, combustion at altitudes around 50,000 ft. but it is felt that this is the lowest figure which is at all acceptable. On the pressure range quoted, therefore, a sea level static pressure of 360 lb./in.² would be required, which would rise to 920 lb./in.² at a sea level Mach number of unity.

Having thus determined the operating range, the flow number $[(\text{gall./hr.})/\sqrt{P}]$ of the fuel system follows automatically. In the instance quoted it is 146. Now experiment has shown that the approximate flow number of a plain orifice is given by the expression $(32d)^2$ where d is the diameter of the fuel jet in inches, and the number of holes required can thus be calculated. For the case under review, there would be 360 holes at 0·020 in., 150 at 0·030 in. or 90 at 0·040 in., or some combination thereof. With this arrangement of holes, fuel must be spread throughout the gas in a way that gives the optimum efficiency at all conditions.

The stability limits of gutter type baffles close in with decrease in pressure and increase in velocity. In any given system, this latter quantity does not vary greatly, but the pressure varies over a wide range, being lowest for the light-up case at altitude.

If good light-up is to be obtained, coupled with flame stability as the fuel is turned on, and the final nozzle opened, then it is essential that the operating point on the baffle stability loop shall be the optimum. This means, that for reheat temperatures below the stoichiometric maximum, an even distribution of fuel throughout the tailpipe is not required; the fuel must be injected selectively so that every inch of stabiliser operates under its optimum stability condition. This may mean—and in fact usually does—that the gas temperature profile at the final nozzle is hot in the centre and cool on the outside, involving some small loss in performance.

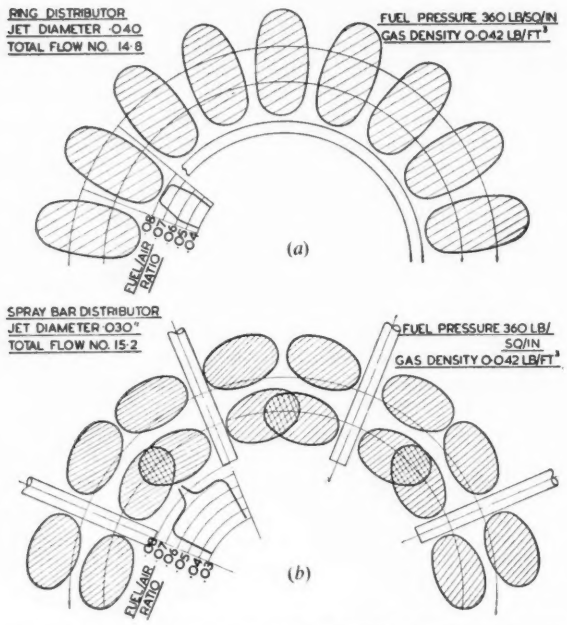


FIGURE 17. Comparison of fuel distribution from spray bar and ring fuel distributors.

Unfortunately, this is unavoidable, but it does have some merit in that the walls of the tailpipe tend to run under rather more favourable conditions than would otherwise be the case, and the need to fit a heat shield is delayed. In practice the fuel is injected to provide a number of bands of fuel and air mixture, each of which feeds a stabiliser, and each adjusted to give the optimum stability characteristics. This requiries an accurate knowledge of the gas flow conditions in the tailpipe, which can only be obtained by traversing the actual engine. When this information is available, fuel jet positions and sizes can be adjusted to give the desired mixtures.

Two techniques are available for fuel injection after the turbine. The first uses spray bars inserted radially into the tailpipe injecting fuel tangential to circles co-axial with the engine; the second uses fuel rings co-axial with the stabilisers and injects fuel radially inwards or outwards.

There are merits in both schemes, but on average it is felt that the ring distributor is probably slightly better. In Fig. 17(*a*), which is approximately to scale, the mixture strength around the stabiliser can be evened out to be almost completely uniform by moving the fuel jets slightly nearer, and the excess of fuel removed by alteration in the hole size and injector pressure. With the spray bar arrangement, (*b*), the burner pattern shown will persist since the jets are bound either to intersect or to leave a gap. In particular the blank space corresponding to the spray bars is difficult to remove unless the fuel is injected some distance upstream of the stabiliser, giving a long mixing time. There will, therefore, tend to be rich and weak zones around the stabiliser, which, even if not serious enough to upset the overall efficiency, may have a deleterious effect on stability.

For very high injection rates, however, where complete and thorough mixing to stoichiometric ratios is desired, a combination of both methods has proved good, since it gives optimum spread of fuel throughout the gas stream.

It has been suggested by various authorities that injection upstream of the turbine not only gives better atomisation and mixing as the fuel and air pass through the turbine, but that it also permits combustion to take place without any artificial aid to stabilisation. In other words, the fuel ignites more or less spontaneously as it passes into the tailpipe, and combustion then continues by eddy mixing in the turbulent gas stream passing to the final nozzle. Further, it is claimed that the injected fuel cools the turbine nozzles and rotating blades, thus permitting higher combustion chamber temperatures. Such a scheme was tried on a Ghost engine, which was run under conditions which gave some outlet swirl from the turbine. The thrust increase was about 10 per cent., and the reheat combustion efficiency 50 per cent. The impact of the hot streams of gas on the bullet support fairings was evident, but in this particular case a stream of cool gas was sandwiched between the flame and the fairing. If positioning of the fuel injectors is bad, the flame may envelop the fairing, stabilisation will occur and the fairing will burn away. A typical example of this kind of failure is shown in Fig. 18.

Tailpipe and inner cone buckling is common due to combustion occurring in the stagnant boundary layer. In all probability this boundary layer combustion is

FIGURE 18. Condition of inner cone support fairing after using pre-turbine fuel injection when turbine outlet whirl is present.

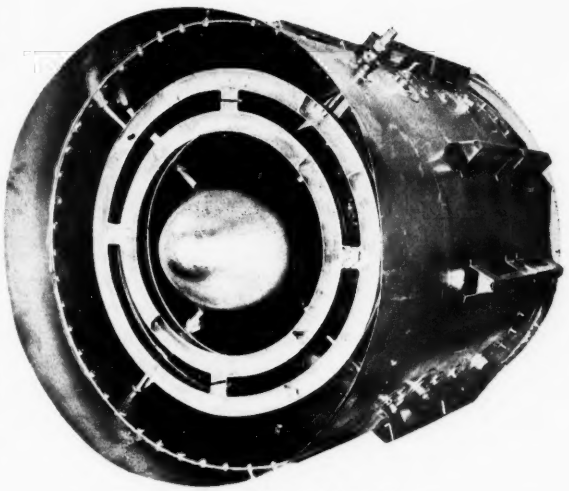


FIGURE 19. Typical multi-stabiliser.

acting as a stabilising piloting region, giving such combustion as does occur, but having a rather unfortunate effect on the sheet metal walls.

The concept of pre-turbine injection appears fundamentally wrong. It assumes that the temperature of the gases leaving the turbine is always high enough to maintain combustion in the tailpipe, that no combustion will occur during passage through the turbine and that stability will be unimpaired with changes in flight conditions. Since it is known that a drop in temperature even on the test bed can result in non-ignition of pre-turbine fuel, the effect at altitude will almost certainly be similar. The only realistic application is one where, on a single-stage turbine, appreciable overheating of the basic engine is permitted, and steps are taken to protect the tailpipe from over-heating, distortion and burning. Even then equivalent or better results can often be achieved from an orthodox scheme with no additional penalty increase in weight or complexity.

4.3. STABILISERS

The two most important parts of any reheat system from a combustion point of view are the fuel injection system and the flame stabilisers. To obtain good combustion, and by that is meant a steady flame with wide stability limits, it is essential to provide a small region where the mean gas velocity can be reduced below the flame speed and where the initial stages of combustion may proceed in a comparatively leisurely manner. The resulting small, very hot region will then mix into the surrounding fuel/air mixture and combustion will proceed until the flame is either quenched by intermingling cool gases, until the local mixture strength passes outside the stability range, or until combustion is complete.

At the moment, the most successful methods of stabilisation are quite orthodox. Some form of baffle is introduced into the gas stream to provoke an eddy reversal and local recirculation and the flame is held to this baffle. If the mixture in the eddy zone should become non-combustible, due possibly to variations in either air flow or fuel flow, then the flame will go out. Several forms of stabilising baffle are in current use, ranging from a multiplicity of small flat plates or cones to a grid of circular gutters, interconnected in a framework as shown in Fig. 19.

Experience has indicated that this latter arrangement is as good as any, and a great deal of effort has been expended in examining the characteristics of stabilisers of this form both from pressure loss and combustion aspects. Generally speaking, the aerodynamic characteristics are pretty well known; the combustion process is in anything but this happy position.

To examine the losses associated with stabilisers, a simple air flow rig was evolved which gave the loss coefficients of a wide variety of gutter shapes, and investigated the effects of blockage (the percentage of tailpipe area occupied by the stabiliser), incidence, shape and size. This work was done without reference to the combustion characteristics of the various gutters and had as its object the provision of design data only.

Figure 20 shows that the principle parameters are the gutter included angle and the blockage ratio. The U-gutter is included in the picture, since it has important applications and strictly speaking may be classified as a V-gutter with 0° included angle. Surprisingly enough it does not deviate greatly from the main curve and certainly gives the lowest loss for a given width.

In the majority of actual reheat systems a multiple stabiliser is used, the gutters being either co-planar or staggered. Tests for a given blockage show that the losses of such a system give slightly lower values than those shown on the curves. Changes in the stagger, pitch or incidence of the stabilisers make little difference and such effects can quite safely be neglected. An increase in the size for any given blockage makes only a very small change in the loss coefficient.

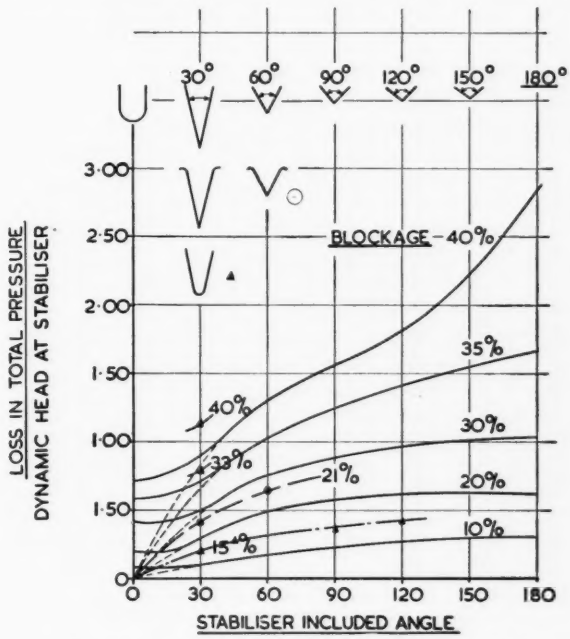


FIGURE 20. Pressure losses incurred by reheat stabilisers.

155122

To verify these results a considerable number of engine tests have been analysed and are presented in Fig. 21. On average these appear about one per cent. higher than the detail stabiliser tests predict, but it must be borne in mind that these test figures are based on measured wall static pressures, and not on traverses; that no allowance is made for skin friction—admittedly very small—or the presence of fuel injectors; and that they are the difference of an overall loss which is measured, and a diffuser loss which is calculated from separate rig results. On average, therefore, it is considered that the agreement is reasonable, and that Fig. 20 is a fair basis on which to predict the losses of any given system.

5. Combustion

A number of very interesting papers have been published in the last few years on combustion in high speed gas streams behind stabilisers. In general, work has been undertaken on homogeneous gaseous mixtures, and though realistic velocities have been attained, in some cases up to 1,000 ft./sec., inlet gas temperatures have been more applicable to ram jets than reheat. From a general point of view this is probably not particularly important since the high temperature of the reheat gas will aid rather than obstruct the combustion process. On the other hand it makes it difficult to apply such information directly to problems of reheat.

The mechanism of the combustion process is now fairly well understood. A region of eddy reversal is formed behind some sort of baffle, such as a flat plate, V-gutter or a cylindrical rod, and this wake serves to stabilise the flame. Presupposing a uniform fuel/air mixture the initial stages of combustion take place in the circulating region of the wake. These heated gases then accelerate up to and past the speed of the unburnt gases, and the velocity gradients so formed generate vortices on the interface between burnt and unburnt gases, and combustion thus proceeds throughout the mixture. There is a drop in static pressure as the flame spreads, and on completion of combustion the total to static pressure relationship has been changed in such a way as to give the increased Mach number shown on Fig. 1.

From this very general conception, the importance of the eddy region immediately behind the stabiliser can be seen. If the flow in this region is, for any reason disrupted, or should the mixture be either so weak or so rich as to give an inadequate temperature rise, then there will be insufficient heat generated in the initial stages of combustion to propagate the flame throughout the mixture, and extinction will occur. The amount of heat generated is a function of the size of the eddy zone which, in its turn, is directly influenced by the size of the stabiliser, and to a lesser extent, by its shape. Experiments are in hand at the moment to determine the exact effect of stabiliser shape on stability, and even though it is probably small, any gains in this direction are well worth while.

In a paper by Longwell, Cheveney, Clark and Frost, the stability criteria of a number of baffles have been

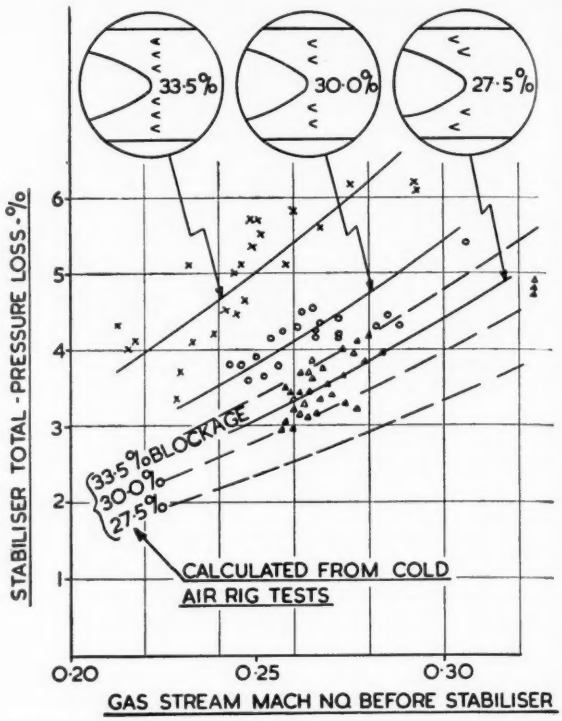


FIGURE 21. Correlation between gutter loss characteristics and engine test results.

correlated on the basis of the ratio of the stabiliser width or diameter to mean gas velocity. The average velocity in a reheat system varies between 400-600 ft./sec. which, for the 1·5 in. wide stabiliser, considered to be about the optimum size, gives a ratio varying between 31×10^{-5} and 21×10^{-5}. The curves published in the paper mentioned* show that at these velocity parameters the stability range under atmospheric pressure conditions is virtually constant and has reached its optimum value. Below 20×10^{-5} the limits tend to close.

The effect of pressure has also been examined by the author of this paper, and it is stated that provided velocity parameters of the order quoted are retained, stability limits do not vary greatly even at pressures as low as 2·9 lb./in.² abs. At the light-up condition of 60,000 ft. Mach number 0·9, the tailpipe pressure is slightly higher than this and thus, provided adequate stabiliser dimensions are retained, there seems no reason why a reasonably stable combustion system should not be evolved. In practice, however, the admission of liquid fuel into a high velocity gas stream, requires some form of injector and despite one's best efforts, the fuel cannot be admitted evenly; it inevitably comes in alternate rich and weak patches. Further, droplet evaporation and rate of diffusion of the fuel into the surrounding gas stream will vary with conditions in the tailpipe, and the effect of the velocity profile at the stabiliser must also have some effect. While the authors of published

*Third Symposium of Combustion and Flame and Explosion Phenomena, 1949.

works do give an overall picture, it is unfortunately a little optimistic in that it presupposes ideal conditions and one must anticipate a certain amount of deviation in practice. There is little doubt that accurate information on the behaviour of stabilised flames using liquid fuel injected into the gas stream is very necessary, and such work is being undertaken at the present time.

The information which the author feels to be most badly needed, is the rate of temperature rise and the rate of spread of the flame for various gas velocities and air/fuel ratios. High inlet temperatures, of the order of 700°C., must be used if truly realistic conditions are to be obtained and the effects of the various techniques of fuel injection must be examined in detail. It is not easy to measure flame temperatures of upwards of 2,000°C. to obtain preliminary information, but a simple technique has been adopted whereby a number of sintox rods are arranged across the flame and the rod temperature gradients measured by means of an optical pyrometer. While it is expected that relatively large experimental errors will occur with this arrangement, the results have not been unduly inconsistent.

In parallel with this technique, a great deal of gas sampling has been undertaken. During the later stages of the combustion process, this is very accurate, and the local air/fuel ratio, combustion efficiency and temperature rise can be estimated. In the main, they agree with the figures obtained by pyrometry. During the early stages of combustion however, the local mixture strength is very rich and combustion is incomplete; somewhat serious errors have arisen under these conditions and experiments in the analysis of such mixtures are still under way. Reasonable success has already been achieved, and it is not anticipated that the development of a suitable process will present undue difficulty.

One other interesting point arises from this stabiliser work which relates to the practice of foreshortening the end of the inner cone and using this as a piloting stabiliser. Within reason the technique is good, but there are a number of snags. Among these is the fact that unless diffusion is efficient and the air flow down the surface of the inner cone good, breakaway will occur upstream of the cut away portion. In this event, there is no organised flow pattern, and the normal process of eddy reversal will not occur. Without this, the flame will not stabilise, and there will be inefficient burning with poor stability characteristics and long flame.

With a cut-off inner cone combustion can often be improved by increasing the diameter of the cut-away portion. If this process is carried too far, however, the eddy reversal ceases to be compact and there will be a rather random region of turbulence left in the middle of the cone. This will produce the same characteristics as were produced with diffuser break-away and there will again be poor stability and long flame.

These troubles are particularly noticeable if an attempt is made to shorten the bullet either to give increased burning length or reduced weight and in very short reheat installations, the author has found little benefit from a cut back inner cone. If, however, plenty of length is available, then it does have some merit.

6. Ignition

So far no mention of ignition has been made, but this can be a major problem. Two techniques are available, either direct electrical ignition by high tension or high energy spark, or by a "streak" where a small quantity of fuel is injected into the combustion chamber, where it ignites, the flame then passing through the turbine and down the tailpipe to the reheat stabilisers.

Both these techniques have been tried with varying success on Goblin and Ghost engines. The electrical system functions reasonably well, but leads and connections adjacent to the hot tailpipe give trouble. The relatively low voltage of the high energy system has some advantage although it has not been conclusively demonstrated that the high energy spark offers anything over the commoner and simpler high tension spark in so far as reheat ignition is concerned.

By far the simplest scheme is streak injection. Here a metered quantity of fuel is injected upstream of the turbine through a plain jet, and provided the turbine entry temperature is high enough, ignition of the reheat system invariably occurs; out of a recent series of 150 lights on the test bed, there were no failures. Despite these advantages, however, this technique may not be applicable to all modern high rated engines due to multiplication of the turbine stages. The cooling effect, as the gases pass through the turbine, coupled with dispersion of the fuel into the air stream could well lead to extinction of the streak. Even if this does not occur, placing the streak flame accurately in respect to the stabilisers will almost certainly be more difficult.

7. Screech

During the course of both reheat and ram-jet development, one of the most persistent troubles has been the onset of a high frequency vibration which has become generally known as "screech." It is characterised by a peculiar violence, and its onset is invariably followed by rapid mechanical failure. This failure evinces itself in the tearing of the sheet metal, or if the screech is only mild, persistent breakage of bolts or slackening of nuts.

While there must be a pattern in the phenomenon, it has so far proved impossible to generalise; it has been experienced in low temperature installations running at only 15 per cent. thrust increase and at high thrust boosts where outlet temperatures of upwards of 2,000°K. have been attained. Despite a great deal of work by many people the exact mechanism of this troublesome phenomenon is not yet known. None the less, a certain amount of knowledge has been accumulated and an attempt will be made to summarise the findings up to the present.

Before doing this it is worth mentioning the various forms of combustion instability which appear in gas turbine installations. The commonest is a rather rough vibration of low frequency and modest amplitude occurring when the turbine nozzles are unchoked. In this case it is possible that the whole air system vibrates as an organ pipe from intake to final nozzle, and that combustion over-richness induces a resonant condition

somewhat on the lines of a singing flame. The well known rumble experienced during engine starting and in the early stages of acceleration is probably of this type.

A second form of instability on reheat systems running at high air/fuel ratios is once again of low frequency, and could very well be due to organ piping of the tailpipe alone. It is associated with local over-richness around the stabiliser, and is a precursor of rich extinction. It has been experienced on both the test bed and in flight, and the mechanism is thought to be due to the spasmodic and sudden combustion of local sections of the mixture followed by a quiescent period while the exhaust gases escape and fresh mixture is supplied, when the cycle repeats. This repetitive process may or may not excite gas resonance but it will produce roughness, instability and ultimately extinction.

With the third form of vibration, namely screech, there seems to be little doubt that it is either a longitudinal or transverse gas vibration in the exhaust stream. The amplitude can be very high, and pressure variations of over $\pm 7{\cdot}0$ lb./in.^{2} have been measured on Ghost and Goblin installations. It is considered unlikely, however, that the sheet metal of the tailpipe is in resonance with the gas frequency, and the failures are almost certainly due to forced vibration.

Calculation of the frequency is difficult owing to the rapidly changing conditions of both velocity and temperature as the gases pass from the turbine to the final nozzle. The shape of the stabilisers and their position relative to the tailpipe walls, the amount of blockage, the air/fuel ratio and the combustion efficiency all take part in determining the vibration characteristics of the gas stream at any particular instant. Approximate calculations however, do give some guide, and it can be shown that the frequency of the fundamental organ pipe mode is of the order of 100-300 cycles/second, assuming the pipe closed at one end and open at the other, between 250 and 750 cycles/second for the fundamental transverse mode and 450 to 1,300 cycles/second for the first harmonic of the transverse mode depending on the temperature of the gases and, in the latter case, on the diameter of the tailpipe.

In attempts to provide experimental evidence many vibration measurements both with and without reheat have been undertaken and have shown pressure-pulsations with a frequency range of 60 cycles/second to 1,200 cycles/second. Tests made by various experimenters, some of whom have used small scale apparatus, and others complete engines, have demonstrated that screech is due to either longitudinal or transverse vibrations in the tailpipe, and fair evidence has been produced on both counts. The position is far from clear, but on balance it would seem that screech is a transverse rather than a longitudinal vibration.

The mechanism by which screech is excited is, probably, not dissimilar to rich extinction instability. A pressure pulsation is set up in the gas stream which alters the local air/fuel ratio. This causes a fluctuation in the rate of heat supply and sets up a pressure wave which reflects back through the gas stream, and the whole process thus tends to be self supporting; if this pulsation excites an appropriate mode of vibration then screech will result. Alternatively radiation from the flame front may cause the unburnt mixture upstream flowing into the combustion region to ignite spontaneously, causing the flame to move slightly upstream. Its new position is, however, unstable, and the flame returns almost immediately to its normal position. Spontaneous ignition again occurs and an impulsive force is thus once more introduced into the gas stream.

While either of these mechanisms may cause screech, both are a little indefinite, in that the excitation frequency is not of necessity equal to the natural frequency of the gas column. The coincidence or otherwise of the forcing frequency and the natural frequency of the gas stream appears to be either purely coincidental, or the phenomenon is such that, being triggered-off by a random pulse, it becomes self-supporting.

An alternative possibility is that the excitation forces result from some disturbance from the compressor, engine combustion system or turbine, and that this may have an appropriate exciting frequency. A number of tests have been undertaken to try to obtain evidence correlating the noise frequencies under mild screech conditions with those obtaining when reheat was not in operation, and measuring the amplitude of the pressure fluctuations. These tests indicated that impulses from the impellor and turbine died out when the gases reached the tailpipe. When screech appeared the frequency was entirely different, a figure of 1,100 cycles/second being recorded in the case tested, with an almost pure sine wave characteristic; the amplitude increased rapidly as screech intensity worsened and it was during these tests that a pressure fluctuation of ± 7 lb./in.^{2} was experienced. This was not sufficient to cause serious mechanical damage to the tailpipe over quite a long period of running, which gives some idea of the magnitude of the forces involved when severe screech develops.

While all the above conjectures are interesting, they really do little towards a real understanding of the phenomenon. No correlation between any forcing

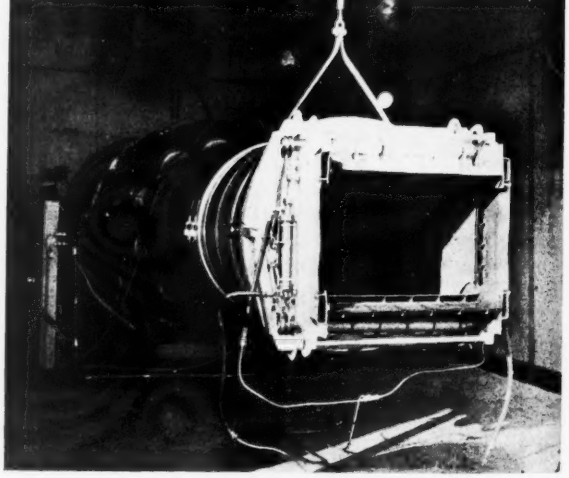


FIGURE 22. Rectangular variable area propelling nozzle.

FIGURE 23. "Clam shell" two position propelling nozzle.

frequency and the screech frequency has been obtained, the nearest approach to coincidence being the vortex shedding frequency from a stabiliser or baffle immersed in a high speed gas stream. Calculations show a frequency range of between 650 cycles/second and 1,250 cycles/second, depending on the gas temperature and the blockage area, and it is interesting to note the similarity between these figures and those actually recorded. On the other hand it has been stated, that though vortex shedding occurs when the baffle is immersed in a free gas stream, the onset of combustion causes shedding to cease and recirculation is then a steady process. If this is really so, there seems little likelihood of vortex shedding being the cause of the instability, and one must continue to look elsewhere.

Turning now to a somewhat more practical outlook, an analysis of the occasions when screech has been experienced on various reheat installations of Ghost and Goblin engines discloses a number of consistent facts:

(*i*) If the stabiliser is situated near the inner cone, and the design of the diffusing passage is such as to cause early break away, then screech will become pronounced at a very early stage, more or less irrespective of the fuel/air ratio.

(*ii*) If spray bars are used, positioned some distance upstream, screech is much more easily provoked than if the fuel is injected close to to the stabiliser.

(*iii*) Co-planar stabilisers are more prone to screech than if they are staggered.

(*iv*) Screech can be partially suppressed by the inclusion of baffles suitably arranged in a tail-pipe. These do burn off in time but they have a marked effect while they last.

(*v*) The inclusion of a heat shield will often reduce abnormal screech to acceptable limits.

8. Propelling Nozzles

The variable area propelling nozzle is an essential adjunct of any reheat system, and its design and construction have presented a number of mechanical problems of considerable magnitude.

In the early days it was thought that a two-position nozzle with an area variation of the order of 40 per cent. would be sufficient for the normal fighter aircraft and that the primary function of reheat would be to give an increased rate of climb and improved take-off; it was not generally appreciated that reheat would be used during the normal flight routine to accelerate the aircraft to supersonic conditions.

Even the relatively simple requirements of subsonic flight presented considerable mechanical problems. Gas temperatures were high, of the order of 1,600-1,700°K., the weight of the nozzle and its operating mechanism was considerable, and its position at the back end of the engine was undesirable from an aircraft stability point of view.

A number of experimental arrangements were however made, of which the most interesting was probably the square nozzle shown in Fig. 22. This was run with a 20 per cent. reheat scheme and worked exceedingly well; it fell down on the score of weight but it had many virtues and since being built has run hundreds of hours as a piece of test equipment on Ghost engines.

The losses due to the change in shape were found to be negligible, and it would be a pity if the possibilities of using this very convenient form were neglected because of difficulties of design or of blending it into the aircraft construction.

The "clam shell" two position nozzle, now quite well known, was finally adopted as being the most convenient arrangement and a Venom installation is shown in Fig. 23. It gave some trouble originally due to sealing, but by developing the geometry of the actuating linkages to give a clamping effect on the seals when the nozzle closed, a very effective and reliable design was evolved. Nozzles of this type have completed many hours running under reheat conditions at temperatures up to 1,800°K. and have given no trouble. The particular design shown here has the merit that in both open and closed positions the final nozzles are circular, which does eliminate any slight losses which might be incurred from non-uniform profiles. It is also amenable to slight adjustments in closed nozzle area, thus enabling the engine's thrust-temperature characteristics to be easily trimmed.

While this work was reasonably straightforward, the emerging conception whereby reheat was to be used to accelerate the aircraft to supersonic speeds, introduced the need for a more comprehensive nozzle.

In the main, there are two possible techniques for this. The first inserts an adjustable bullet whereby the throat area is changed by moving the bullet forwards and backwards. Disadvantages are the immersion of the bullet in the centre of the hot gas stream which introduces a major cooling and control problem, and the rather bulky construction of the whole assembly.

The second arrangement uses a multiplicity of interleaving fingers for both the propelling nozzle and the inducer cuff. By a suitable arrangement of interconnecting linkages and jacks, these fingers are made to move somewhat like an iris shutter on a camera, and

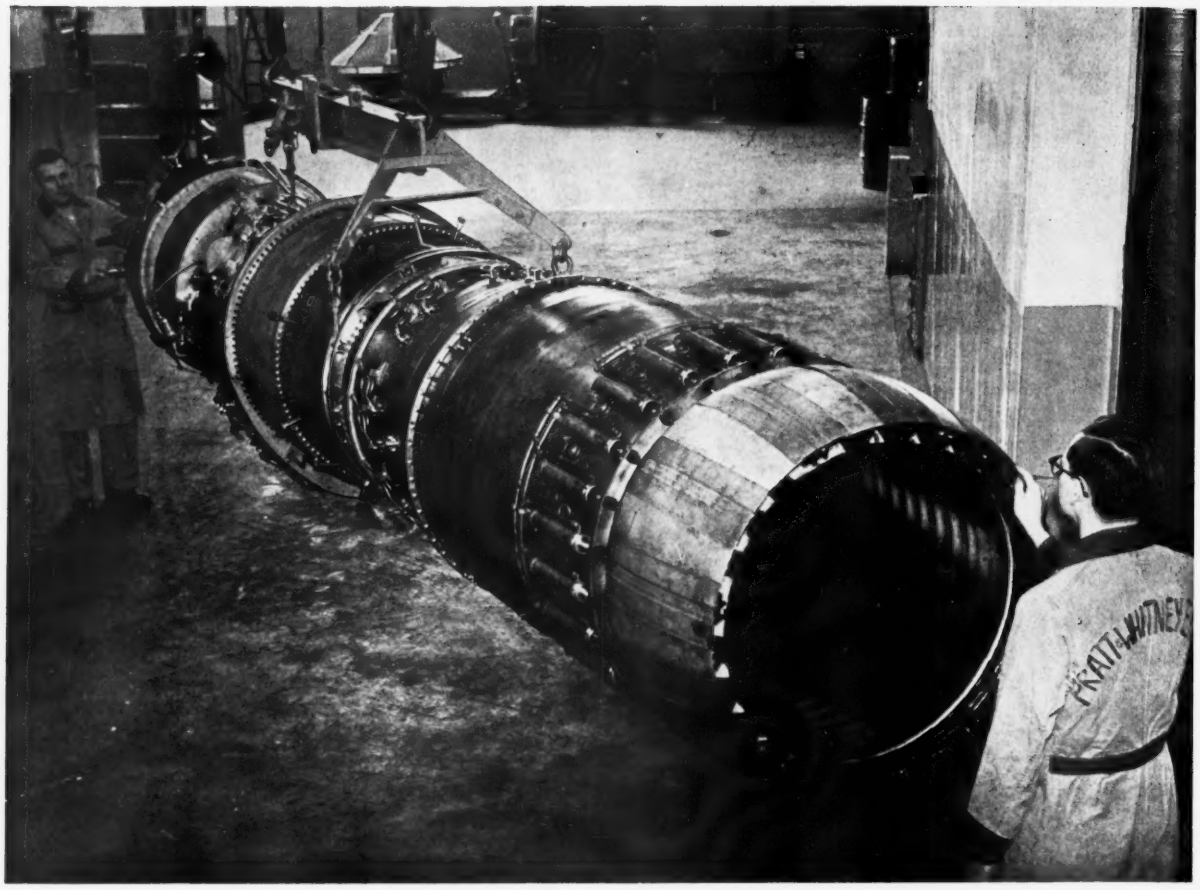


FIGURE 24. Pratt and Whitney J.57 engine with reheat tailpipe. *Courtesy Shell Aviation News*

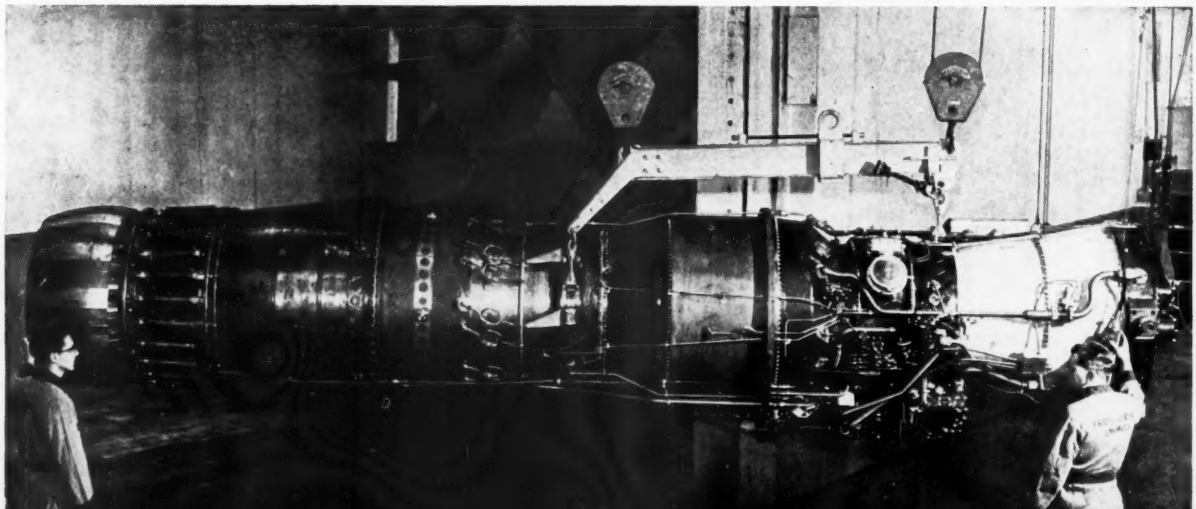


FIGURE 25. Pratt and Whitney J.57 engine with reheat tailpipe. *Courtesy Shell Aviation News*

any predetermined variation in nozzle profile and area ratio can thus be obtained. This design is extremely complex, it is susceptible to jamming due to local distortions, and the sealing problems on the various interleaving faces are formidable. Further, at high thrust boosts, it is absolutely essential to cool the final nozzle irrespective of its construction which introduces yet another major complication. These difficulties are not insuperable, however, and a practical example is the Pratt and Whitney engine shown on Figs. 24 and 25.

There is little doubt that the fully variable nozzle for use at high temperatures presents one of the biggest mechanical problems associated with reheat. There are, of course, other solutions than those outlined above, but a simple solution of the problems of cooling, weight and control, is most elusive. In fact, there seems to be no easy way out, and the complicated mechanisms at present coming on to the test bed may be the only answer.

9. Fuel Systems

The fuel system associated with reheat is not as involved as that on the engine, but none the less, it must be designed carefully, and the quantities of fuel to be handled are considerably greater. In a typical engine of 250 lb./sec. mass flow, for example a reheat fuel flow of the order of 10,000 gall./hr. would be required at a Mach number of 1·5 at sea level. With a simplex injector system at least 1,000 lb./in.^{2} pressure at the burner ring is necessary under full duty conditions, if a reasonable pressure is to be obtained when lighting up at extreme altitudes. Further the pump and control system must be interconnected with the variable nozzle so that optimum engine conditions obtain at all times.

With quantities of fuel of this magnitude, displacement pumps of any kind are heavy and cumbersome, and the associated gear drives occupy valuable engine space. The centrifugal pump driven by an air turbine has the advantage of compactness and mechanical independence of the engine, allowing it to be positioned more conveniently. Disadvantages are the difficulty of obtaining the fuel pressure, except at high pump speeds, the bulk of the air ducting necessary to convey the turbine air from the engine to the unit, and the low efficiency. It is possible that the efficiency will be improved with development, and that the overall figure of about 30 per cent. now being attained may be lifted appreciably. It is unlikely however, that very high efficiencies will ever be attained, and 50 per cent. is probably the optimum.

The power requirements are quite high, and for a 250 lb./sec. engine reheated to 2,000°K. a maximum of about 400 B.H.P. is necessary under sea level conditions at 1·5 Mach number. This can be obtained from about 6·5 lb./sec. air, after due allowance has been made for losses in the ducting, which implies a loss from the engine of approximately 1·0 per cent. If the pump were driven direct, there would be a power saving of some 150-200 h.p. but for the engine under consideration, this is a very small percentage of the transmitted power, and the slight drop in economy introduced by the use of a turbine pump is more than compensated by the saving in weight and adaptability.

A serious criticism is the possibility of over-speeding should the fuel supply fail. It is now a requirement that some form of overspeed device be incorporated in the unit, preferably, aerodynamic, whereby upon removal of the load from the pump the r.p.m. increase is kept to a safe value. Unfortunately, aerodynamic overspeed devices which involve a spoiling of the turbine efficiency, usually result in some loss at normal conditions, and the unit must be designed to withstand the overspeed condition. There is thus a strong argument in favour of an overspeed device which will control the speed to a definite maximum. This will result in a lighter unit since the overspeed condition is only slightly faster than the design speed, but of course the risk of the governor failing just when it is required must be accepted.

There are two alternative techniques for controlling the fuel flow from the unit, either by throttling the air supply to the turbine, or by throttling the fuel supply from the pump. The characteristics of a centrifugal pump of this type are fairly flat in the sense that the pressure does not change materially with fuel flow at a given speed. It does therefore lend itself to fuel volume control. Air control is clumsy and insensitive, and a throttle in the fuel line is probably the preferable method.

Air is supplied to the pump turbine from the compressor outlet and the pressure ratio across the pump turbine is therefore proportional to the overall pressure ratio across the engine compressor. Since the engine turbine nozzles are always choked and since the engine turbine entry temperature is constant, the air mass flow through the pump turbine is proportional to the pump turbine entry pressure, which in turn is proportional to the engine compressor outlet pressure and the engine mass flow. This implies that the turbo-pump could be left to run free, without any air control, and that it will supply a quantity of fuel very nearly proportional to the mass flow through the engine, which is what is required for reheat. There will of course be inconsistencies due to variations in combustion efficiency, turbine efficiency and so on, but these can be corrected by adjusting the fuel flow by an automatic throttle in the reheat system.

With this in mind therefore, the main control parameter is the engine pressure at compressor outlet and the trimming parameter should be turbine outlet temperature. It is true that any temperature on a jet engine is difficult to measure accurately and consistently due to changes in bias and combustion chamber traverse. On the other hand, jet pipe temperature is the accepted way of controlling present day engines, and there are indications that the use of annular combustion chambers will effect a considerable improvement in both the radial and circumferential temperature distribution at the turbine outlet. Nevertheless, as a safeguard, a number of thermocouples connected in parallel or series whichever was deemed best, would obviously be used. There thus seems no real reason why the turbine outlet temperature should not be the controlling parameter for reheat fuel flow, and it has the added advantage that a variable datum is easy to incorporate, which will permit

adjustments to the engine allowing optimum conditions to be obtained at all times.

There is one point which must be watched very closely however. On a number of installations a long tailpipe will be necessary, which may have to be necked down to pass through a spar or to avoid some obstruction in the wing or fuselage. A condition could arise here where opening the final nozzle will move the choking point upstream to the necked-down section, and under conditions of low speed flight or on the test bed the turbine outlet temperature may prove insensitive to changes in the final nozzle area.

There are many variants which can be introduced into the reheat fuel system and there is little doubt that given appropriate development, it will soon become as complicated as the present engine system. Basically, however, it appears to be fairly simple and such difficulties as do exist should not be too hard to overcome.

10. Conclusions

In this paper the author has endeavoured to summarise the present day development position on reheat as he sees it. It is not thought that there will be any material disagreement with the general findings as regards the engine, but there must be many points of dissension regarding techniques of diffusion, stabilisation and combustion; there are many major design problems associated with variable nozzles and it is inevitable that there will be differences in approach and emphasis depending on the particular applications confronting the individual concerned. None the less, the general status of reheat is now appreciated and largely understood and it is thought that a system can be designed for most applications, provided the fundamentals are kept in mind and the impossible is not attempted.

ACKNOWLEDGMENT

The author would like to express his thanks to the de Havilland Engine Company and the Ministry of Supply for permission to publish this paper, and to his colleagues who have been so very helpful in its preparation.

DISCUSSION

PROFESSOR A. D. BAXTER (Professor of Aircraft Propulsion, College of Aeronautics, *Fellow*): The lecture which Mr. Edwards gave five years ago set down the principles and problems of reheat, and tonight he had taken the story somewhat farther. He looked on what he had given them now as a progress report. He re-read the 1949 lecture, partly because he hoped to find Mr. Edwards contradicting himself, but he laid down conditions then and predicted what should be done, and tonight he had shown how well it had been done.

Five years ago Mr. Edwards put the weight penalty for reheat at about 20 per cent. of the main engine weight. Tonight he had mentioned weight problems once or twice, but had not indicated what the weight penalty was. Was that because the figure today did not agree with the 20 per cent. he gave previously? Was it better or worse?

At the beginning of this lecture it was stated that in 1949 reheat was in its infancy in Great Britain; the President had referred to the promise of this system, and he thought also Mr. Edwards rather implied that the Americans had a great deal more knowledge of it than we had, but did he think that they still knew more? He wondered if Mr. Edwards showed the J.S7 reheat tailpipe because of that.

In any case he thought it ought to be recorded that the 1949 reheat infant was then by no means new-born. It was conceived in Great Britain and was born at least five years earlier; but he supposed, as with many another brain child, they were inclined to neglect it until others showed its capabilities. He suspected that in 1944, when they were playing with reheat, they might have been very ignorant of the conditions necessary for this baby to develop; but at least they did have reheat working in those days, with all the jetpipe failures and combustion stability problems that Mr. Edwards had since experienced. That might not be of much comfort to him or to others who had struggled with reheat since that time, but at least it might encourage them to know that it was a practical job which actually operated in flight. He himself flew with a reheat system giving 25 per cent. boost in flight almost ten years ago.

It was a far cry from the puny jets they had then to the hypothetical giant engines which the author envisaged. In this connection he would emphasise the importance of the low tailpipe Mach number and the problems that went with it. They had gas velocities of the order of 1,200 ft./sec. leaving the turbine, and they had to be slowed down to 400 ft./sec. The normal bullet and exhaust cone was not a very effective diffuser and in any case it would not bring the velocities down sufficiently to do more than (say) 50 per cent. of the diffusion, so that they were left with the tailpipe to do the rest of it. That meant that the cross-sectional area of the jetpipe must be increased; and if his figures were correct it would increase, for the conditions Mr. Edwards envisaged, to something approaching the outside overall diameter of the engine. Then they had an engine which was practically a long tube, and that, he thought, might bring installation problems with it. Mr. Edwards had mentioned the necking of the jetpipe and the various consequences which that might have. He could foresee that there might be other problems.

In this connection he wondered whether any thought had been given to a conical combustion chamber instead of a parallel one. By that means they might be able to keep down the fundamental combustion loss, and he saw no reason why they should not be able to use a tapered jetpipe. Possibly the problem of the large diameter of jetpipe came in there; the final cross-section of such a

pipe might well be larger than that of the rest of the engine and so introduce even greater installation difficulties.

With regard to tailpipes, could Mr. Edwards give an idea of the L/D ratio required for reheat? In the heat transfer diagram, Fig. 11, there was a length of 7 ft., and he imagined the heat shield there in any circumstances was getting fairly close to its limiting temperature. If they considered this hypothetical engine and made a guess that the tailpipe diameter was 44 in. and the L/D ratio $2\frac{1}{2}/1$, that would give a tailpipe length of 9 ft., and unless improved cooling could be introduced it suggested a limit to the engine size for reheat.

DR. E. S. MOULT (Chief Engineer de Havilland Engine Co. Ltd., *Fellow*): A commendable point in the paper was a description of the experimental methods employed and a frank account of the troubles encountered. He hoped subsequent speakers would also discuss those aspects because by sharing difficulties and experiences they could make progress.

The advantages to be gained from reheat depended on the aircraft application and particularly on the speed of flight. Referring to the top curve (2,000°K.) of Fig. 9 they saw that a test-bed boost of, say, +40 per cent. became +70 per cent. at Mach No. 1·0 in the stratosphere, +100 per cent. at Mach No. 2·0 and +220 per cent. at $M=3{\cdot}0$. Thus, at a speed of Mach No. 2·0 the net thrust of the un-reheated engine was doubled and at Mach 3·0 it was more than trebled. Those were stupendous gains which could not be neglected by the aircraft designer.

The disadvantages—and there were always penalties—were the weight and space of the afterburner and its heavy fuel consumption. However, for short-period operation at high speeds reheat more than earned its keep, considered simply on the basis of thrust obtained against the additional weight of installation plus fuel.

From a thermodynamic point of view it would be preferable to burn fuel in the engine itself, rather than in the jetpipe. There was always surplus oxygen in the combustion chamber if they dared inject the additional fuel and raise the working temperature. However, they were limited by the materials and stresses of the turbine and every designer of a fighter engine already ran his engine at as high a temperature as was permissible.

The future would see the development of high temperature engines using cooled turbines in some form or other in an endeavour to reduce the overall fuel consumption when using reheat. As temperatures rose in the engine, the scope for reheat would diminish and, in the limit, when all the oxygen was burnt in the engine, there was nothing more they could do about it! The difficulties were great and there was no doubt that they would see an increasing use of reheat for high speed flight for many years to come.

F. M. OWNER (Deputy Chief Engineer, The de Havilland Engine Co. Ltd., *Fellow*): He thought Mr. Edwards had done very well indeed to point out that there were certain laws of nature which said that they had to have a certain size of jetpipe if they were to burn a given quantity of reheat fuel, and he would be the last to suggest that they could circumvent those laws. Indeed, he thought Mr. Edwards might have added to his exposition by warning the aircraft designer that the jetpipe might have to be appreciably larger than the engine if they had to go to temperatures of the order of 2,000°K.

During the past ten years they had been working on a mechanism of combustion, both in the engine and in the reheat pipe, which had remained substantially unaltered throughout that period. Broadly speaking, they had been unable to effect stabilisation of the flame by any means less crude than (colloquially) putting up an umbrella for the flame to lurk under. They did not seem to know any other method of slowing down the gas than putting in a device which achieved a great deal of drag in the process of creating the low velocity stream in which alone combustion could be effected. Did Mr. Edwards foresee any possibility of a fundamental attack on this aspect of the problem, and could they achieve combustion not only in the reheat system, but perhaps eventually in the engine, by some means less destructive of pressure head?

K. T. FULTON ("The Aeroplane," *Graduate*): On the larger and more powerful engines were they reaching a stage at which the expansion ratio across the propelling nozzle was sufficient to warrant the use of a convergent-divergent nozzle, as opposed to the present use of a purely convergent nozzle?

He noticed that all Mr. Edwards' installations made use of fuel injection and flame stabilisation equipment at the end of the bullet inside the tailpipe. Was that purely the result of the dimensions of the tailpipe installation, as in the Vampire or Venom, or did he think there was an advantage in having it farther down the tailpipe?

A. V. CLEAVER (de Havilland Engine Co. Ltd., *Fellow*): He would like to ask a question about the future use of reheat, not so much as an auxiliary, but as a pre-ordained part of the flight plan right from the beginning, as it was likely to be on those aircraft which were designed to operate at a Mach number of 2·0 or more. Did Mr. Edwards think there would be any particular advantage in using some special high-density fuel, such as a metallic powder, for the reheat system, remembering that a very large volume of ordinary fuel would have to be carried? With the reheat tailpipe one would seem to have a combustion system which would be peculiarly suited to that.

The same point arose with the pure ram jet. There was no rotating machinery downstream of the combustion zone which might be damaged by the products from such a combustion process, and he would be interested to know if Mr. Edwards thought it might have a future for this application.

WING CDR. R. MILROY HAYES (R.A.F. (Retd.), *Associate*): That afternoon he had been interested to hear Field Marshal Viscount Montgomery (in a lecture at the R.U.S.I.) talking about "a look through a window

at World War Three." He had emphasised how vital it was for them and for all who were working with them in N.A.T.O. and in other alliances to "get cracking" with their defences and aircraft so that they could react effectively at once if they were attacked: and had said that if they were attacked thermo-nuclear weapons would be used in their defence.

The Royal Aeronautical Society represented the first line of brain power applied to aircraft development. Reheat became very important in that development. In this country they were very short of money, materials, manpower, and machine capacity, and reheat gave something which allowed them to produce just that little bit of extra power in the air with less weight penalty than some other developments, less expense and less expenditure of production capacity. Therefore it was something to be encouraged. If any in the audience could give them the mere germ of an idea it would be useful.

There had been reference to diffusers. So far as he could see, they had the pipe and the bullet. Why should it not come from the bullet itself?

He hoped that all the young people present, if they had ideas, would talk about them. The whole history of the Society had been one of progress and the putting forward of modern ideas. The Royal Society of Arts might be regarded as an august body, yet the younger people spoke at their meetings. There were many young people present at this lecture.

R. S. HOOPER (Hawker Aircraft Ltd., *Graduate*): Mr. Edwards had mentioned that at a Mach number of 3·0 the turbine outlet pressure would be equal to the pressure in the aircraft intakes, and suggested that at higher speeds the engine would only be getting in the way. Had he given any thought to the possibility of increasing the proportion of thrust from his department—once the engine had reached its limiting mass flow—by passing intake air direct to the reheat pipe? In other words, although at Mach numbers above 3·0 they would like to have a ramjet engine, the need to take off and accelerate required a turbo-jet. Was there any possibility of converting the power plant progressively from predominantly turbo-jet to predominantly ram-jet as the speed increased? The method suggested required the by-passing of large quantities of air and would probably be difficult installationally; were there other objections?

DR. H. COHEN (*Associate Fellow*): He would like to refer to the problem of the over-heating of the jetpipe wall. Could Mr. Edwards say if he had given consideration to the possibility of purposely keeping the hotter part of the reheat in the centre of the jetpipe? This would employ a principle similar to that put forward for running turbines at a higher mean inlet temperature by arranging a controlled temperature distribution which would result in only the less highly stressed outer portions of the blades being subjected to the highest temperatures. In the reheat application the temperature distribution would have to be such that there would be a uniform temperature at the highest level over the major portion of the jetpipe cross-section falling off rapidly to the lowest possible in a narrow annular region adjacent to the jetpipe wall. The success of such a method would, of course, depend on the extent to which the heat transfer to the wall was divided between radiation and convection.

A further possible method of reducing the wall temperature might be the use of the reheat fuel as a coolant by passing it through a double-skinned jetpipe wall. However, the danger of cracking of the fuel might preclude its use in this way.

G. J. HUDSON (Joseph Lucas (Gas Turbine Equipment) Ltd.): He would like to refer to a development which might, to some extent, work in opposition to the reheat projects, and that was the trend towards higher turbine inlet temperatures. There were signs that temperatures of the order of 1,500°K. and upwards might be considered in the coming years. There would therefore be less oxygen left in the jetpipe gases, making it less worth while, on the one hand, to use up what remained and, on the other hand, it would be more difficult to do so due to the severe dilution with products of combustion. He wondered if Mr. Edwards felt that jetpipe reheat would then become a thing of the past.

THE PRESIDENT: Of course, designers of aircraft would view with some concern the references to larger diameter jetpipes, and it was difficult, in the light of Mach numbers such as had been mentioned, to consider the fuselage in the case of a small single seater fighter having a larger diameter than the front.

Points that also ran through one's mind were—would reheat work successfully at over 60,000 ft.? Again, what about thrust reversal? The problem of the nozzle was undoubtedly a tremendous one mechanically. The question of fuel consumption also arose, and in any system of reheat they must consider the problem of drag, as this could absorb too high a proportion of the extra power resulting from the use of reheat. Up to the present he thought they had proved that extra power in the form of a bigger engine was better than the same power *via* a smaller engine plus reheat.

E. L. SMITH (National Aeronautical Establishment Canada, *Grad.R.Ae.S.*) *contributed:* One of the aspects of reheat which might have been enlarged upon was fuel injection upstream of the turbine.

In addition to conventional reheat systems mention was made from time to time of reheat systems employing fuel injection upstream of the turbine. These systems avoided the use of a flame holder either by using the turbine itself as a flame holder or by depending on the self-ignition properties of the fuel to cause ignition and combustion just downstream of the turbine. It was generally agreed that it was difficult, if not impossible, to achieve satisfactory performance over a wide range of ambient conditions with this type of reheat.

A third scheme had been under investigation for some time at the National Aeronautical Establishment and under sea level conditions at least, had been giving quite satisfactory performance.

In this reheat system fuel was sprayed directly onto

the rotating turbine blading to achieve a useful degree of blade cooling. Under these conditions the fuel was not heated sufficiently to cause spontaneous ignition and a fairly conventional flame holder together with a pilot fuel spray and spark igniter was therefore mounted at the entrance to the reheat combustion section.

The benefits accruing from this form of fuel injection, in addition to turbine blade cooling, were thorough mixing of reheat fuel and air, and a reduction in required flame holder area due to pre-heating of the reheat fuel.

Data were not yet available either on the performance of this system on multi-stage turbine engines or at low ambient pressures, but the information thus far obtained was sufficiently promising to indicate that all reheat schemes employing fuel injection upstream of the turbine should not be classified automatically as being fundamentally wrong.

MR. EDWARDS' REPLY

PROFESSOR BAXTER: He did not know what the position would be five years hence, but he would congratulate Professor Baxter on having actually flown with reheat ten years ago. That was a real achievement.

The agreement between his first and second paper was not entirely fortuitous; but he must confess that he had overlooked that he put the weight penalty for reheat at about 20 per cent. of the weight of the engine. He thought that was one of those generalisations one sometimes made without adequate information, which at the time was not available. Nowadays, however, so much depended on the application. If a reheat system to assist take-off was all that was required, this could be designed with a relatively small weight penalty. On the other hand, if the application were one to persuade a fighter to do $2\frac{1}{2}M$, Fig. 25 showed that, as Professor Baxter had said, the tailpipe would have a cross section literally of the same size as the engine.

The next point, concerning the L/D ratio was one of those generalisations that just could not be made. For any type of combustion stabiliser, there was a particular size which gave optimum stability; in the case of the gutter, this size was about $1\frac{1}{2}$ in. wide. If it were smaller, the stability suffered and there was no object in going bigger. As explained in the lecture, the flame would then spread through the gas stream at some given rate, and combustion would be complete shortly after the flames emanating from the various stabilisers intersected. The time—or the length of tailpipe—necessary to achieve complete combustion could be shortened by increasing the turbulence of the gas, or by multiplying the number of stabilisers. Either method would, however, increase the pressure loss, and a balance must always be struck between decreased length or decreased performance.

He did put combustion intensity into his first paper as a parameter, but he now thought that was wrong; it was not one that he would use today. In practice, an average length for the combustion zone was somewhere between 5 and 6 ft., but, as explained before, it could be shorter or longer; either way carried penalties.

The amount of knowledge gained by the Americans was vast in terms of quantity, but he did not think they really knew more about the fundamentals of reheat than they did in Great Britain. The Americans had a great deal more data and practical experience, but as regards technique they were not much in advance, if at all.

The conical combustion system was good from the purely combustion point of view. If the gases could be diffused while they burned, the combustion zone Mach number was kept down, and the losses reduced. On the other hand, the tailpipe diameter increased greatly and he had never had the nerve to suggest a scheme of this type. The weight penalty alone would be enormous.

MR. OWNER: He could see no other practical method of flame stabilisation at the moment. The trouble was that, once more, one was up against a fundamental law of nature whereby the completion of any chemical or physical process under a given set of conditions required a certain time. Basically, all that happened when fuel was burnt in a gas stream was that certain chemical processes were completed. They must, however, be completed within the confines of a piece of tin 9 ft. in diameter and about 6 ft. long, in a stream of gas flowing at some 400-600 ft. per second. This did not allow much time, and therefore the process must be encouraged in every way possible. It must be given a start and this was done by slowing the gases locally and stirring them up. To do this, one provided an "umbrella."

Once the reaction had started, time was still all important in that the mixing of the combustible and unburnt gases was a function of the turbulence generated by the difference in velocity between hot and cold gas streams. If fuel were merely injected into the gas stream and allowed to oxidise, then it might never burn, or if it did, it would need a long time. To do it quickly it must have a start, and must be stirred up, and this meant pressure loss.

MR. FULTON: He had assumed in all curves that the combustion efficiency was 100 per cent. and that the gases were fully expanded; this implied the use of convergent-divergent nozzles. Pressure ratios were about 4 : 1 at Mach No. 1·0, 12 : 1 at Mach No. 2·0 and 20 : 1 at Mach No. 3·0. If the maximum thrust were to be obtained, then a convergent-divergent nozzle was essential. The problem of how to design a nozzle to take full advantage of the expansion ratio was mechanical rather than aerodynamic.

The positioning of the stabilisers at the back end of the bullet was forced on one by restrictions in tailpipe length, when every inch of space must be used. It was much easier to position the stabiliser 2 or 3 ft. downstream of the bullet and to burn the gases comfortably in an evenly flowing gas stream. Positioning them close to the bullet put them in a region of poor velocity profile which could materially upset the combustion stability.

Unfortunately, it was a design which was often forced upon one by the layout of the aeroplane.

MR. CLEAVER: Anything that would give more out of a given space was worth thinking about. In that sense the use of special fuel, if it were to give some advantage in either weight or space saving was well worth having. It was, however, a development which fell into the category of pure research at the moment; it was something they would like to know much more about before its applications could be considered. There were obvious practical difficulties in using any special fuel. He did not mean just changing to another hydrocarbon, and until they had overcome many of the snags which beset them in the present orthodox reheat system, the use of such things as slurries must be looked upon as one of the things that was yet to come.

WING CDR. MILROY HAYES: The suggestion of stabilising the flame from the back end of the bullet was an accepted technique in many present-day applications. For small amounts of reheat it was excellent, but it had disadvantages in that, if the bullet were part of the diffusing system, and the system were short, then breakaway would probably occur at the downstream end. If this did happen, instead of a controlled recirculation necessary for stable combustion, there would be random turbulence, the fuel would burn untidily and a lazy long flame would wander off and disappear out of the back end without doing any efficient work.

The trouble could be overcome by extending the length of the assembly. Thus, if there was plenty of room and if a high degree of reheat were not required, this could be a useful technique.

MR. HOOPER: When aircraft fly at these speeds, it was obvious that, far from being a rather unpleasant adjunct to an otherwise good engine, the engine had become an encumbrance to the reheat system. He had thought of diagrammatically illustrating such a design as Mr. Hooper suggested, but it did not seem entirely relevant to the subject under discussion. It was undoubtedly a possibility, but it did not arise until Mach numbers of about 3·0 were achieved. When this had been done there would be good grounds for considering some such technique.

DR. COHEN: If one were considering reheat temperatures up to about 1,750°K., the technique of holding the flame in the centre of the tailpipe was the one usually adopted. Up to this temperature, it was usually possible to dispense with the heat shield. Above 1,750°K., however, nearly all the air was being used, for combustion the temperature profile tended to flatten at a high value, and a heat shield was essential.

As to the suggestion of fuel-cooling the tailpipe by putting a double skin around it, he did not think it was practical. First, there was the question of weight, relative expansions and strength to withstand the high fuel pressures; second, the fuel would probably boil and third, the formidable fire risk.

With regard to heat transfer, most reheat flames were violet or blue, rather than yellow, and flame radiation was low. Gas velocities and temperatures on the other hand were high, so that the great majority of the heat transfer must be due to convection.

MR. HUDSON: The figure Mr. Hudson quoted appeared somewhat high for the near future, although it might be achieved within the next decade. It was certainly more efficient to burn fuel in the engine rather than in the tailpipe, and if very high turbine temperatures could be tolerated, then the percentage gain from reheat as it was now employed could obviously become less. He felt, however, that reheat would be both possible and profitable for some years yet.

MR. SMITH: The findings on the generally accepted technique of pre-turbine injection, whereby combustion of the reheat fuel was achieved without artificial stabilisation, agreed with their own. Combustion was difficult, and the stability range was narrow and, although Mr. Smith did not say so, screech was easily provoked.

If the technique of upstream injection were applied in connection with orthodox stabilisation, then the advantages claimed by Mr. Smith were, on the face of it, quite real. On the other hand, while spraying fuel on to turbine blades at 1,200°K-1,300°K had, in theory, produced a measure of cooling, it was also quite likely to cause them to crack due to thermal shock. It was inevitable that cooling by the direct injection of liquid must be violent and patchy, and one could not but feel that this was a technique with little to recommend it.

A further point was the difficulty inherent in this system of selective placing of the fuel; if they wished to concentrate fuel in the centre of the tailpipe to obtain small thrust boosts, then the mixture of fuel and air as it passed through the turbine might be so thorough that a relatively rich mixture throughout the whole tailpipe would result before any combustion at all could be instituted. At very high thrust boosts, this had an advantage, and the scheme might work very well.

A third criticism on pre-turbine injection with or without stabilsers, was the likelihood of spontaneous combustion in the boundary layer of the inner cone or outer tailpipe, and it was unlikely that the mere fitment of a stabiliser would prevent damage such as that illustrated in Fig. 18.

Despite these criticisms, and he confessed to being somewhat biased against this method of fuel injection, it was possible that future experiments and development might show it to have peculiar virtues in certain applications. Mr. Smith's experiments were undoubtedly fully justified, and it was possible that from his work and findings many of the virtues of orthodox reheat and pre-turbine injection would emerge and a compact and efficient arrangement result.

TECHNICAL NOTES

Contributions to this Section of the JOURNAL *will be eligible for Journal Premium Awards and will normally be published within two months of being received.*

Buckling and Vibration of Isosceles Triangular Plates having the Two Equal Edges Clamped and the Other Edge Simply-Supported

by

HUGH L. COX AND BERTRAM KLEIN

(Strength Engineers, Douglas Aircraft Company Inc.)

APPROXIMATE SOLUTIONS obtained by the method of collocation[1] are presented for the lowest critical buckling load of an isosceles triangular plate loaded as shown in Fig. 1. Also, the fundamental frequency is given. The base of the triangle is simply-supported and the other equal edges are clamped.

The usual assumptions regarding the bending of thin plates are made. The governing differential equation for the plate loaded as shown in Fig. 1 is

$$D\nabla^2\nabla^2 w - N\left(\frac{a}{h}\right)^2 \frac{\partial^2 w}{\partial x^2} + N\frac{\partial^2 w}{\partial y^2} = 0 \qquad (1)$$

where D is the plate stiffness, N is axial load per unit length, w is deflection, positive downward, and the quantities a and h are dimensions shown in Fig. 1. The boundary conditions are

$$(w)_{y=h} = (w)_{x=\pm\frac{a}{h}y} = 0 \quad . \quad . \qquad (2)$$

$$\left(\frac{\partial^2 w}{\partial y^2} + \nu\frac{\partial^2 w}{\partial t^2}\right)_{y=h} = 0 \quad . \quad . \qquad (3)$$

$$\left(\frac{\partial w}{\partial n}\right)_{x=\pm\frac{a}{h}y} = 0 \quad . \quad . \qquad (4)$$

where n is the normal direction to the lines

$$x = \pm\frac{a}{h}y,$$

and t is the tangential direction of any line. Along a rectilinear edge the term $\partial^2 w/\partial t^2$ is equal to zero. The deflection function

$$w = (\alpha_1 F_1 + \alpha_2 F_2 + \alpha_3 F_3)F_4 \quad . \quad . \qquad (5)$$

where

$$F_1 = 2\sin^2\frac{\pi y}{2h}\sin\frac{\pi y}{h}$$

$$F_2 = 2\sin^2\frac{\pi y}{2h}\sin\frac{2\pi y}{h}$$

$$F_3 = 2\sin^2\frac{\pi y}{2h}\sin\frac{3\pi y}{h}$$

$$F_4 = \left[1 - \left(\frac{h}{a}\frac{x}{y}\right)^2\right]\cos k\frac{\pi}{2}\frac{h}{a}\frac{x}{y}$$

$\alpha =$ generalised coefficient

$k =$ an odd integer,

satisfies equations (2) and (4) exactly and equation (3) only when $x=0$. Selected points for collocation will be along the line $x=0$; therefore, no serious error should result from not satisfying completely the boundary conditions.

If equation (5) is differentiated and the proper derivatives are substituted into equation (1), and equation (1) is evaluated at the points $y=h/2$, $2h/3$, $3h/4$ along the line $x=0$, a third order determinant results. Values of N_{CR} have been determined from the resulting characteristic equation and are shown in terms of the real coefficient β in Fig. 2 by the dotted line. For the case of $h/a=1{\cdot}0$ another solution, which differs from the foregoing solution by about ten per cent., has been obtained by Wittrick[2]; the collocation solution should be reasonably accurate for large values of h/a since the

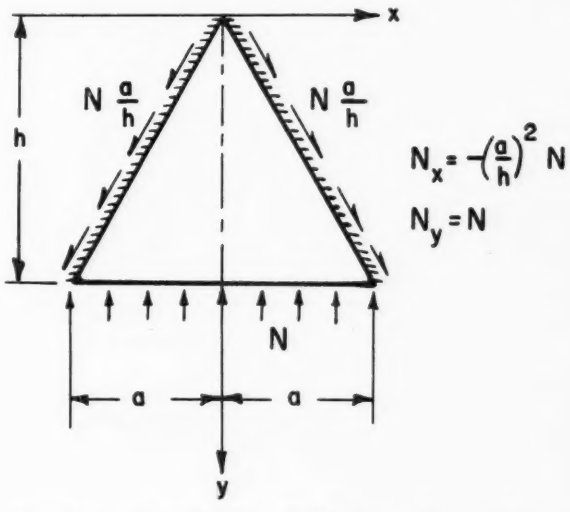


FIGURE 1. Load conditions considered for triangular plates.

Received 3rd January 1955.

triangle begins to approach a segment of a circle. The heavy black line in Fig. 2 appears to be quite reasonable and values of β corresponding to this curve are believed to be sufficiently accurate for aircraft engineering purposes. The additional amount of work required to improve the curve by about one or two per cent. is not deemed worth while in view of assumptions that are generally made regarding boundary conditions, etc.

When the plate is vibrating freely, equation (1) may be rewritten as

$$D\nabla^2\nabla^2 w - \frac{q\omega_n^2}{g} w = 0 \quad . \quad . \quad (6)$$

where q is the plate weight per length squared, g is gravitational acceleration, and ω_n is a natural frequency. The deflection function given by equation (5) may be used again and the collocation method yields a characteristic equation from which the fundamental frequency may be determined for various ratios of the parameter h/a. The dotted curve in the lower part of Fig. 2 represents solutions by the collocation method. Finite difference solutions indicate that the value of β given by the dotted curve for $h/a = 1{\cdot}0$ is slightly too low. The solid adjusted curve is believed to be sufficiently accurate for engineering purposes and for the value of $h/a = 1{\cdot}0$ should be within about two-tenths of one per cent. of the true answer. Extrapolation was used with the finite difference solutions[3].

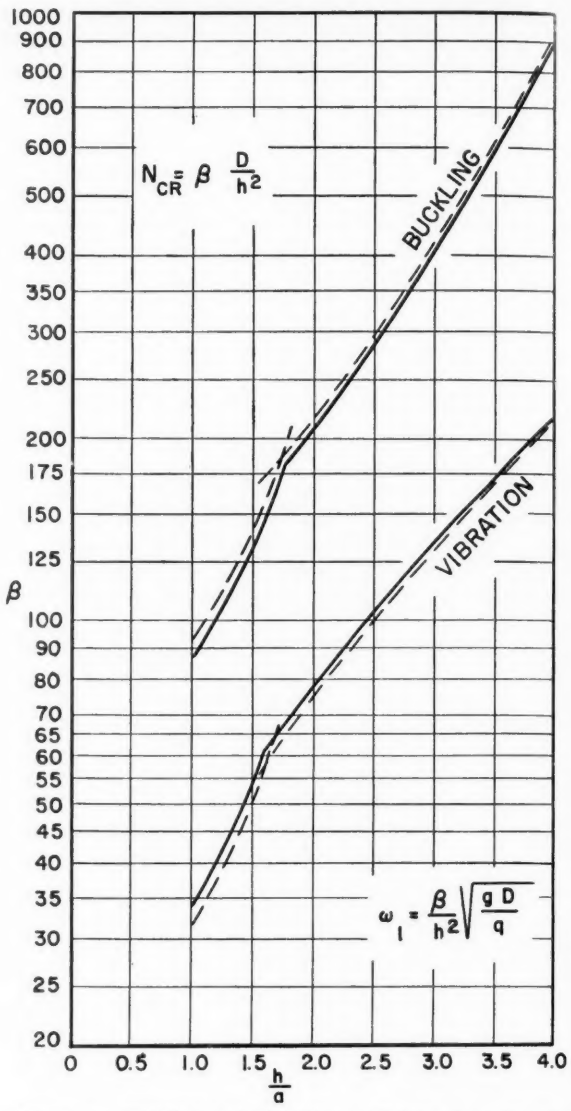


FIGURE 2. Buckling and vibration coefficients for triangular plates.

REFERENCES

1. KLEIN, B. and COX, H. L. (1954). Approximate Structural Analysis by the Method of Collocation. *Journal of the Aeronautical Sciences*, Vol. 21, No. 10, p. 719, October 1954.
2. WITTRICK, W. H. (1953). Buckling of a Right-Angled Isosceles Triangular Plate in Combined Compression and Shear. Department of Supply, Research and Development Branch, ARL/SM 220, Melbourne, November 1953.
3. SALVADORI, M. G. (1951). Numerical Computation of Buckling Loads by Finite Differences. *Transactions of the American Society of Civil Engineers*, Vol. 116, pp. 590-624, 1951.

Generalised Stress-Strain Data for Aluminium Alloys and certain other Materials

by

ANTHONY J. BARRETT, M.S. in A.E., B.Sc.(Eng.), Grad.R.Ae.S.

and

MAUREEN E. MICHAEL, B.A., Grad.R.Ae.S.

(Technical Department, Royal Aeronautical Society)

THIS NOTE investigates some of the methods by which values of stress, strain, tangent modulus, ratio of stress to tangent modulus, and various other data may be estimated from a few known characteristic values on the stress-strain curve of a material. A method is proposed and presented in the form of nomograms which are applicable to cases where the stress-strain curve consists of a finite linear range, which may be quite short, followed by a smooth curve in the post-linear range. The results of comparisons between

Received 5th January 1955

data obtained from the nomograms and that obtained by more conventional processes indicates that the order of accuracy is high. Further, the method is flexible in its application with respect to both the choice and actual numerical values of the characteristic points on the stress-strain curve.

1. INTRODUCTION

In many engineering problems it is necessary, from time to time, to deduce from only a few characteristic values data which would ideally be obtained from a complete stress-strain curve. For instance many handbooks, used in design offices and published by materials manufacturers and others, contain values of Young's modulus and minimum guaranteed, or typical, values of various proof stresses for materials. From these, estimates of strain, tangent modulus or ratio of stress to tangent modulus appropriate to known stress values may be required, or various processes involving integration of the stress-strain curve may have to be carried out. Even when a complete stress-strain curve is available from a special test, the differentiation and integration of it, which may have to be repeated several times, are time-consuming processes. Also, in analytical work involving the use of materials beyond the limit of proportionality, it is desirable to have available a generalised mathematical form of the stress-strain curve in order that the results obtained may be applied to a wide range of actual materials simply by the substitution of appropriate coefficients. These and many other applications will be familiar to the reader.

The requirements which must be fulfilled by a deductive method are many and among the most important are:—

(*a*) *Accuracy.* The accuracy of any analytical method used in engineering work is obviously of prime importance. In the present case it is necessary that the accuracy of the method be at least of the same order as that to which material data is evaluated and recorded.

(*b*) *Flexibility.* The wide ranges of basic composition and heat treatment of materials now in use impose the requirement that the method should be sufficiently flexible to cover a wide range of stress-strain characteristics. In particular the method must be capable of dealing with wide ranges of elastic moduli, stresses and strains. Further, the choice of the characteristics must itself be flexible since practice in this respect varies widely. For example, a method for the deduction of data which relied upon a knowledge of say the 0·5 per cent. and 0·2 per cent. proof stresses as the characteristics, would be of little use in a case where only the 0·2 per cent. and 0·1 per cent. proof stresses were known. Therefore the method must be flexible with respect to both the choice of characteristics and their actual numerical values.

(*c*) *Ease of Application.* The method and presentation should be such that the deduction of data is straightforward and rapid. No matter what the choice of characteristic values might be, it is desirable that the processes involved should be identical in all cases.

Notation

f	stress
ε	strain
f_1, f_2, f_5, f_{ult}	0·1, 0·2 and 0·5 per cent. proof stresses and ultimate stress
E, E_t, E_{sec}	Young's, tangent and secant moduli
s_1, s_2	secant yield strengths in equation (1)
e	$\varepsilon E/s_1$
σ	f/s_1
m_1, m_2	secant gradients in equation (1)
n	shape parameter in equation (1)
f_R, f_R'	reference stresses ($f_R > f_R'$)
$\varepsilon_R, \varepsilon_R'$	non-proportional strains corresponding to f_R and f_R' (*see* Fig. 1)
A, B, m	parameters in equation (2)
Δ	error

2. SOME EXISTING FORMS OF GENERALISED MATERIAL DATA

Probably the most widely known form of generalised material data is that contained in the Royal Aeronautical Society's Structures Data Sheets[1] 00.02.01, 02 and 03 which give values of tangent modulus and ratios of stress to tangent modulus for a number of standardised stress-strain curves. These have been considered in a recent Technical Note by A. C. Nicholls[2] and further detailed discussion is not necessary here. However, although the data sheets mentioned have proved of great value they do not fulfil all the requirements outlined in the Introduction to this paper, particularly in view of the number and types of material now in use or coming into use.

Reference 1 uses as characteristic values for a stress-strain curve E, f_2 and f_{ult}, additional restrictions being imposed by the use of $E = 10 \times 10^6$ lb./in.^{2} and $\varepsilon_{max} = 0{\cdot}14$ throughout. In aircraft work, post-elastic properties up to approximately f_5 are of particular interest and it is hardly to be expected that f_{ult} would have a very definite bearing upon the shape of the stress-strain curve in this range. It follows that there could be considerable variation between the mathematical curve and curves for actual materials, even though all passed through the same values of f_2 and f_{ult} and had the same

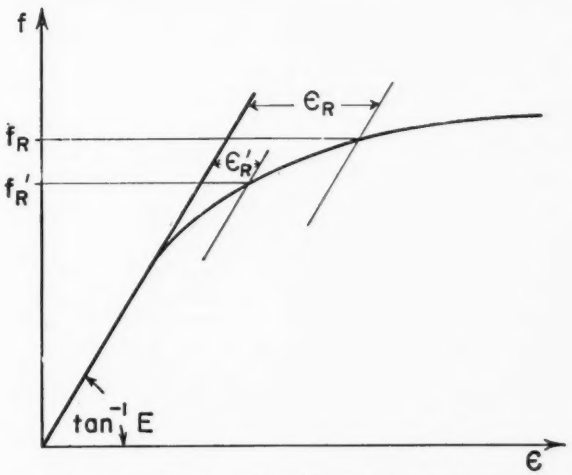


FIGURE 1. Characteristic values for stress-strain curve.

value of E. The method of presentation, which is in terms of stress, strain and the ratio f_2/f_{ult}, makes for easy extraction of the data if one of the standardised stress-strain curves coincides with that for the actual material and the results obtained will obviously be accurate. If there is no such coincidence, an involved interpolation is usually necessary. Further, as the data is only presented for one value of E and fixed values of f_2, the range of applicability of the method is strictly limited. Ref. 2 describes modifications which can be made to overcome some of the shortcomings of the method, particularly with regard to accuracy, by a more realistic choice of characteristic values.

A mathematical expression for stress-strain curves which has found considerable favour among theoreticians, particularly in the U.S.A., is the Ramberg-Osgood expression[3] originally quoted in the non-dimensional form

$$e=\sigma+\left(\frac{1-m_1}{m_1}\right)\sigma^n. \quad . \quad . \quad (1)$$

The secant yield strength is defined as the ordinate of the intersection with the stress-strain curve of a line through the origin having a slope equal to m_1E, m_1 being a constant. By considering a range of materials in common use in 1943, at the time of publication of Ref. 3, it was decided that a value of $m_1=0{\cdot}7$ was a suitable mean value giving $s_1 \simeq f_2$ and this value has persisted in the use of the original Ramberg-Osgood expression up to the present time. The shape parameter n is determined, in the case of the original expression, by the use of a second reference stress s_2 defined as the ordinate of the intersection with the stress-strain curve of a line through the origin having a slope equal to m_2E, m_2 being taken as 0·85. The value of $m_2=0{\cdot}85$ was chosen as a mean between $m_1=0{\cdot}7$, corresponding to the first reference value s_1, and the value 1·0 corresponding to the elastic portion of the curve. Although the expression gives very good representations of actual stress-strain curves the choice of reference stresses leaves much to be desired. Tables of characteristic values for materials do not give s_1 or s_2 as defined. The range of characteristic values available varies considerably and it is therefore desirable to leave the choice of reference stresses completely free.

The Barrett modification of the Ramberg-Osgood expression, as used in Ref. 4, has also been discussed by Nicholls[2]. Briefly, the modification retains the desirable qualities of expression (1) but introduces reference values which are completely general. The modified expression in its most general form is:—

$$\varepsilon=A\left(\frac{f}{f_R}\right)+B\left(\frac{f}{f_R}\right)^m. \quad . \quad . \quad . \quad (2)$$

As in the case of the Ramberg-Osgood expression, this modified form is made to yield a curve which simulates the initial slope of the stress-strain curve $(df/d\varepsilon)_{\varepsilon=0}=E$, in which case $A=f_R/E$. If two reference stress values are chosen as f_R and f_R' and the permanent or, more strictly, non-proportional strains corresponding to these stresses are ε_R and ε_R', then

$$\varepsilon=\frac{f_R}{E}\left(\frac{f}{f_R}\right)+\varepsilon_R\left(\frac{f}{f_R}\right)^n \quad . \quad . \quad (3)$$

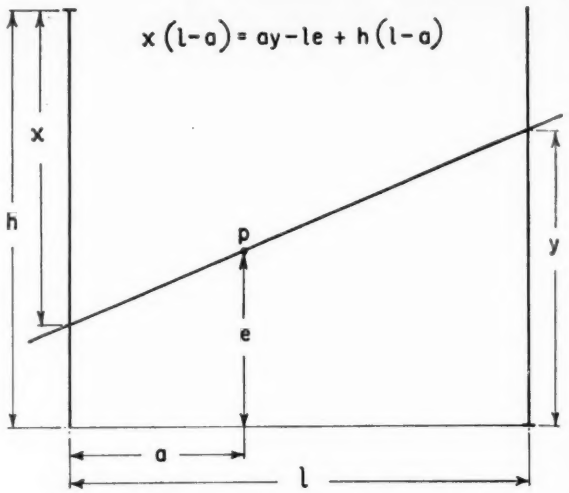


FIGURE 2. Geometry of the nomograms of Figs. 4 and 5.

where $$m=\frac{\log \varepsilon_R-\log \varepsilon_R'}{\log f_R-\log f_R'}. \quad . \quad (4)$$

It is also convenient to specify $f_R>f_R'$. The characteristic values are illustrated in Fig. 1.

Expression (3) may be differentiated to give

$$E_t=\left\{\frac{1}{E}+\frac{m\varepsilon_R}{f_R}\left(\frac{f}{f_R}\right)^{m-1}\right\}^{-1}. \quad . \quad (5)$$

Further, since

$$E_{sec}=f/\varepsilon$$

$$E_{sec}=\left\{\frac{1}{E}+\frac{\varepsilon_R}{f_R}\left(\frac{f}{f_R}\right)^{m-1}\right\}^{-1}. \quad . \quad (6)$$

3. PRESENTATION

Having decided upon a possible expression for the simulation of a range of stress-strain curves, the next step in the development of a method employing the expression would be an investigation of how nearly it coincides with points on actual stress-strain curves other than those used as reference points. However, the accuracy of the method as a whole depends not only upon the basic expressions, but also upon the way in which the resulting data is to be presented; therefore it is desirable to consider at this stage the method of presentation.

The parameters involved in expressions (3), (5) and (6) are numerous and the variations of their numerical values too great to allow of a reasonable presentation in straightforward curve form, desirable though this may be. For a complete coverage of modern materials a set of families of curves would be required. Two stages of interpolation would be necessary, one between the various families and another between the individual curves of the interpolated family; a difficult and time-consuming process in which errors would necessarily accumulate. The only adequate solution lies in the presentation of the work in nomogram form.

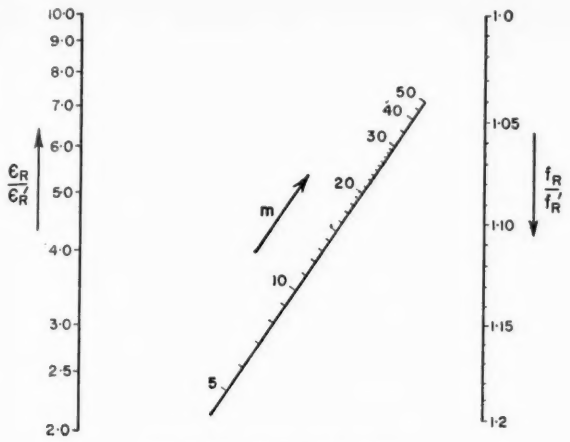


FIGURE 3. Nomogram for m.

Re-writing expressions (3), (5) and (6) in non-dimensional form,

$$\frac{\varepsilon E}{f_R} = \frac{f}{f_R} + \frac{\varepsilon_R E}{f_R}\left(\frac{f}{f_R}\right)^m \quad . \quad . \quad (3a)$$

$$\frac{f}{E_t}\frac{E}{f_R} = \frac{f}{f_R} + \frac{m\varepsilon_R E}{f_R}\left(\frac{f}{f_R}\right)^m \quad . \quad . \quad (5a)$$

$$\frac{f}{E_{sec}}\frac{E}{f_R} = \frac{f}{f_R} + \frac{\varepsilon_R E}{f_R}\left(\frac{f}{f_R}\right)^m \quad . \quad . \quad (6a)$$

In all cases, for fixed values of f/f_R and m, the parameter on the left hand side is linearly related to the coefficient of $(f/f_R)^m$. Now if the left hand side and the coefficient of $(f/f_R)^m$ are represented by parallel scales, the intersections x and y on these of a line passing through a fixed point p, are linearly related (*see* Fig. 2). Several points such as p may be plotted for the same x and y scales, appropriate to various values of f/f_R and a fixed value of m. A locus of points p may then be drawn. If the procedure is repeated with a new x scale, drawn parallel to the original scales so that l assumes some new value, a new locus of points p may be plotted which corresponds to a new value of m. The resulting series of loci appropriate to a range of values of m may then be connected by contours of f/f_R and a carpet in f/f_R and m is formed. The resulting nomogram is shown in Fig. 4.

Readers unfamiliar with the production of nomograms may find this construction process somewhat involved. It is fortunate, however, that the actual use of the nomogram is very straightforward as the numerical examples illustrate. To facilitate the evaluation of m, expression (4) may be put in nomogram form as illustrated in Fig. 3.

EXAMPLE 1

To find the stress corresponding to a strain of 0·009 for a material in which

$E = 15{\cdot}8 \times 10^6$ lb./in.^{2}
0·5 per cent. proof stress = 91,600 lb./in.^{2}
0·2 per cent. proof stress = 88,900 lb./in.^{2}

Then

$f_R = 91{,}600$ lb./in.^{2} $\quad f_R' = 88{,}900$ lb./in.^{2}
$\varepsilon_R = 0{\cdot}005$ $\quad \varepsilon_R' = 0{\cdot}002$
$\varepsilon = 0{\cdot}009$
$\varepsilon_R/\varepsilon_R' = 2{\cdot}5$ $\quad f_R/f_R' = 1{\cdot}030.$

A straight line adjoining 2·5 on the left hand scale, and 1·030 on the right hand scale of Fig. 3, intersects the m scale at 31·0.

$$m = 31{\cdot}0$$

$$\frac{\varepsilon E}{f_R} = \frac{0{\cdot}009 \times 15{\cdot}8 \times 10^6}{91{,}600} = 1{\cdot}552$$

$$\frac{\varepsilon_R E}{f_R} = \frac{0{\cdot}005 \times 15{\cdot}8 \times 10^6}{91{,}600} = 0{\cdot}862.$$

The construction is shown on the nomogram of Fig. 4. Point a is located on the rectangular grid of $(\varepsilon E/f_R)$ and m. Point b is located along the axis of $(\varepsilon_R E/f_R)$ and the line ab is drawn. Point c is located by the intersection of ab and the carpet line for $m = 31{\cdot}0$ interpolated between $m = 30$ and $m = 35$.

Point c gives $f/f_R = 0{\cdot}986$ and $f = 0{\cdot}986 \times 91{,}600 = 90{,}300$ lb./in.^{2}.

It will be noted that expressions (3*a*), (5*a*) and (6*a*) are similar. The nomogram of Fig. 4 could be used to represent (5*a*) by using $(f/E_t)(E/f_R)$ in place of $(\varepsilon E/f_R)$ and $(m\varepsilon_R E/f_R)$ in place of $(\varepsilon_R E/f_R)$. Similarly, it could be used to represent (6*a*) by using $(f/E_{sec})(E/f_R)$ in place of $(\varepsilon E/f_R)$, the coefficient of $(f/f_R)^m$ being the same. While this is satisfactory in the case of (6*a*), in most actual problems the numerical values of the parameters in (5*a*) are not amenable to the use of the same nomogram. It will generally be necessary to plot a second nomogram for (5*a*) with larger numerical values for the two linear scales, as shown in Fig. 5. Again, the simplicity of the operation of this nomogram is illustrated by a numerical example.

EXAMPLE 2

To find the stress in the material specified in Example 1 when $f/E_t = 0{\cdot}076$.

From the values given in Example 1,

$$\frac{m\varepsilon_R E}{f_R} = \frac{31{\cdot}0 \times 0{\cdot}005 \times 15{\cdot}8 \times 10^6}{91{,}600} = 26{\cdot}7$$

$$\frac{f}{E_t}\frac{E}{f_R} = \frac{0{\cdot}076 \times 15{\cdot}8 \times 10^6}{91{,}600} = 13{\cdot}1.$$

The construction is shown on the nomogram of Fig. 5. Point a is located on the rectangular grid of $(f/E_t)(E/f_R)$ and m.

Point b is located along the axis of $(m\varepsilon_R E/f_R)$ and the line ab is drawn. Point c is located by the intersection of ab and the carpet line for $m = 31{\cdot}0$ interpolated between $m = 30$ and $m = 35$. Point c gives $f/f_R = 0{\cdot}975$ and $f = 0{\cdot}975 \times 91{,}600 = 89{,}300$ lb./in.^{2}.

In both nomograms the scales for $(\varepsilon E/f_R)$, $(\varepsilon_R E/f_R)$, $(f/E_t)(E/f_R)$ and $(m\varepsilon_R E/f_R)$ are linear and may be extrapolated if necessary to cover an awkward example.

4. ACCURACY

The accuracy of the method is now considered. It will be remembered that the data is required for use in three ways, as a stress-strain expression, as the first differential of the stress-strain curve (for tangent modulus applications, etc.) and in the integrated form for areas and first moments of areas of the stress-strain curve. The last of these applications has been considered in Refs. 4 and 7. It is sufficient to note here, in respect to these integrative processes, that if the expressions give a satisfactory representation of stress versus strain, the accuracy of integration will be of a high order.

The following examination may be made of the proximity to which expression (3) represents actual material stress-strain curves.

The expression has been made to represent the initial slope of the stress-strain curve and to pass through two known points on the curve, $[f_R, (\varepsilon_R + f_R/E)]$ and $[f_R', (\varepsilon_R' + f_R'/E)]$. If a third known point on the actual curve is $[f_R'', (\varepsilon_R'' + f_R''/E)]$ and the mathematical curve of expression (3) gives a stress corresponding to a non-proportional strain ε_R'' of f_R'' $(1+\Delta)$ then

$$\log(f_R/f_R') = \frac{\log(\varepsilon_R/\varepsilon_R')}{\log(\varepsilon_R''/\varepsilon_R)} \{\log(f_R''/f_R) + \log(1+\Delta)\}.$$

By use of this expression it is possible to find how near the mathematical curve passes to a third proof stress value when it is made to pass through two known proof stress values.

126 sets of f_5, f_2 and f_1 were used, taken from Ref. 5. These values are appropriate to a very wide range of typical tensile and compressive stress-strain curves for aluminium alloys. In Table I the number of cases in which the mathematical curve gave a value of the third of these proof stresses to within 2 per cent. is shown. There are two points of note. Firstly, 11 of the 126 sets of values showed inflexions and did not correspond to stress-strain curves of the same form as equation (2). However, all 126 sets are considered and the results of Table I reflect the accuracy of the method when applied without prior selection of the data. Secondly, the accuracy is seen to be greatest when the data extracted corresponds to points on the stress-strain curve between points of coincidence of the actual and mathematical stress-strain curves. This is a result typical of any such process; interpolation invariably being more accurate than extrapolation. Bearing in mind that a high degree of accuracy is obtained when stress values, appropriate to the data extracted, lie between f_R and f_R' and that this decreases the further these stress values deviate from this range, the accuracy of the method in respect to the representation of stress and strain is satisfactory.

TABLE I

f_R	f_R'	f_R''	*Number of cases in which* $0{\cdot}02 > \Delta > -0{\cdot}02$
f_5	f_2	f_1	106
f_5	f_1	f_2	122
f_2	f_1	f_5	92

The accuracy of the method when applied to the evaluation of data involving E_t has been checked in the following way.

From actual stress-strain curves values of E_t were obtained in the conventional manner at various stress levels, and values of f/E_t calculated. These values of f/E_t and the known values of proof stresses and Young's moduli were used in the nomogram of Fig. 5 to evaluate values for f for comparison with the stress values taken from the actual curve. Various pairs of proof stress values were used as the characteristics f_R and f_R', the results being as shown in Table II. Similar checks have been made independently in Ref. 6 where the method is applied to a number of aluminium alloys, titanium alloys and a magnesium alloy. In all cases when the data

TABLE II

Material Properties				*By measurement from stress-strain curve*		*Nomogram value of f for measured value of* f/E_t		
E	f_1	f_2	f_5	f	f/E_t	$f_R=f_2 \mid f_R'=f_1$	$f_R=f_5 \mid f_R'=f_1$	$f_R=f_5 \mid f_R'=f_2$
$9{\cdot}6\times10^6$	13·2	13·7	14·8	12·4	0·0062	12·3	12·4	12·1
				13·2	0·0150	13·1	13·1	13·1
				13·7	0·0326	13·6	13·9	14·0
				14·1	0·0411	—	14·2	14·2
$10{\cdot}5\times10^6$	38·1	38·9	40·2	36·5	0·011	36·4	37·3	37·3
				38·1	0·021	37·5	37·9	38·3
				39·0	0·065	39·0	39·0	38·9
				39·5	0·113	—	39·6	39·7
$10{\cdot}4\times10^6$	66·0	67·9	70·6	63·0	0·0121	61·8	62·5	60·7
				66·0	0·0287	65·7	65·7	64·2
				67·9	0·0566	67·9	67·9	66·7
				69·0	0·0767	—	69·2	67·8
$10{\cdot}7\times10^6$	87·6	90·3	92·8	83·5	0·0139	83·0	84·9	84·0
				87·6	0·0258	86·7	87·0	86·8
				90·3	0·0602	91·2	89·7	89·2
				91·7	0·0834	—	90·9	90·5

All units of stress are lb./in.$^2\times10^{-3}$.

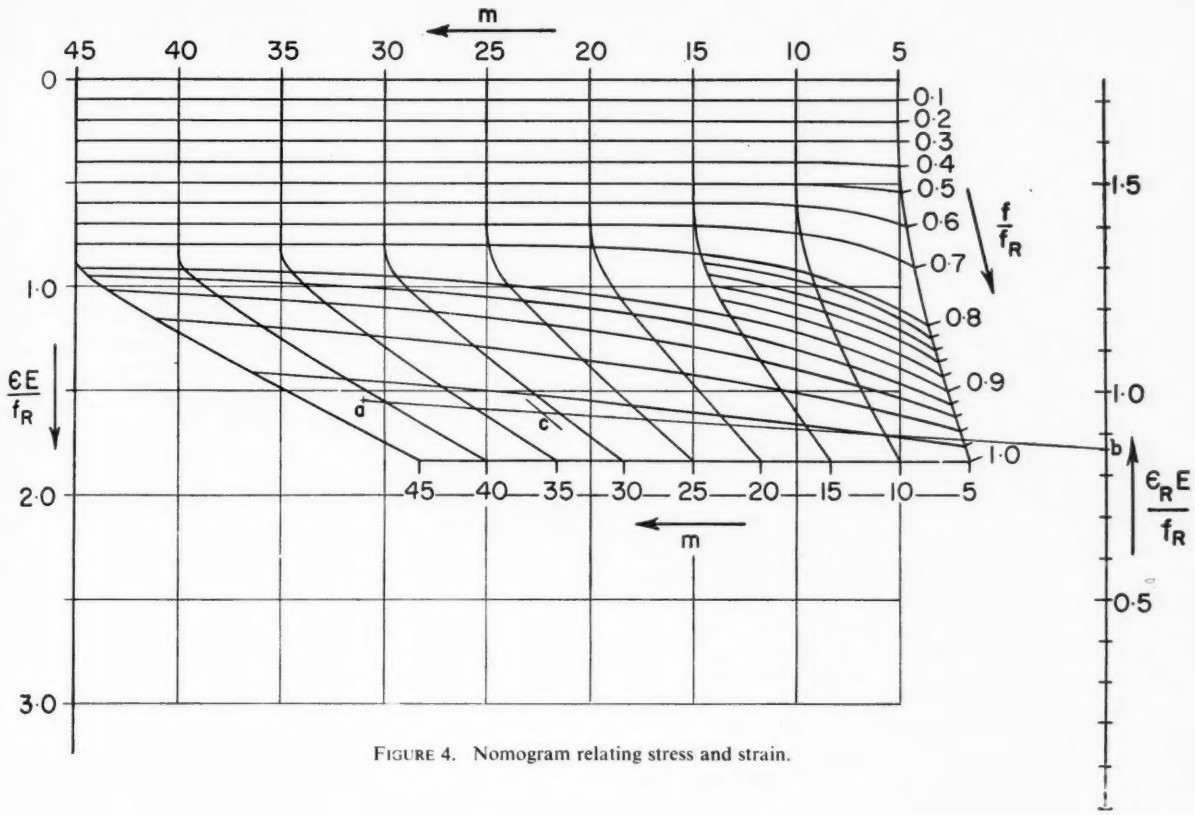


FIGURE 4. Nomogram relating stress and strain.

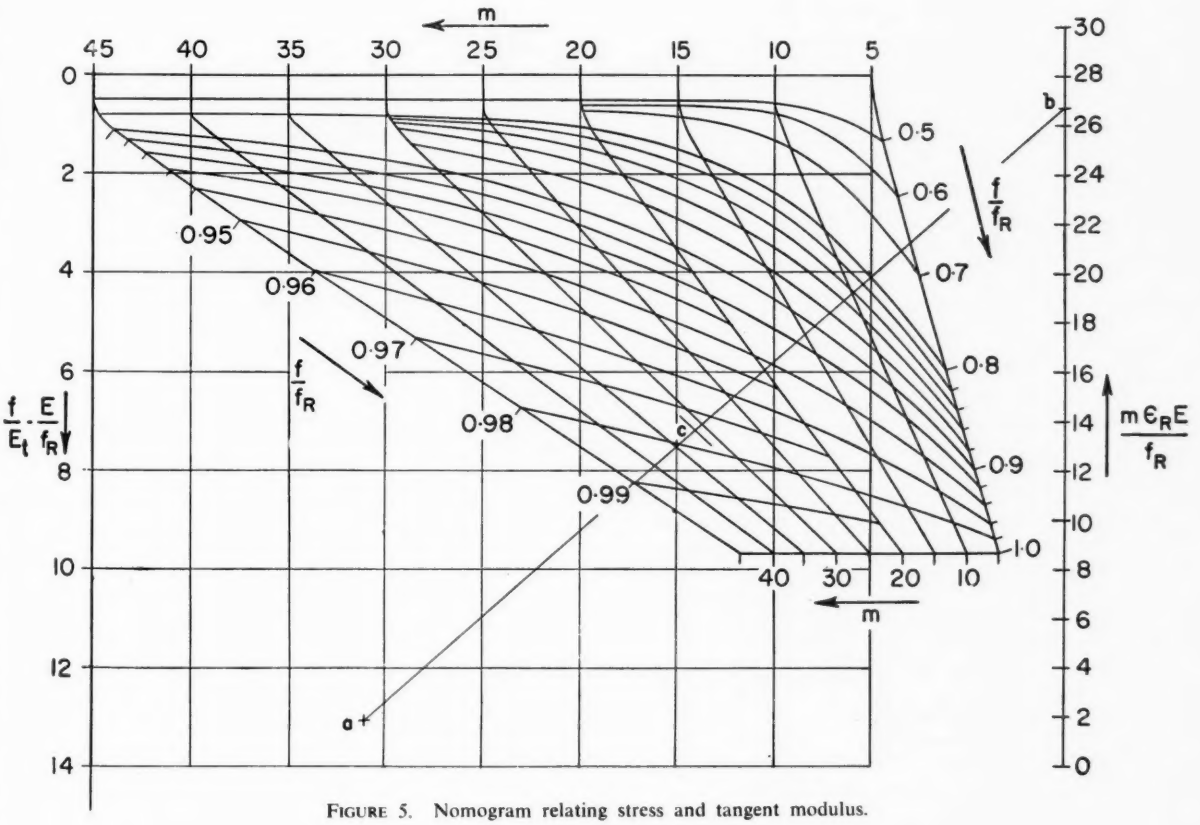


FIGURE 5. Nomogram relating stress and tangent modulus.

extracted lay in the range f_R to f_R' the error was less than about 1 per cent. and when the data extracted lay outside this range the error was usually less than 2 per cent. The worst error recorded was 6 per cent. in a case where the data extracted was appropriate to a stress value only slightly beyond the limit of proportionality of the material, the reference stresses used being f_5 and f_2. Since these errors are of only the same order as those involved in obtaining values of E_t by geometrical means the accuracy of the proposed method would seem to be satisfactory.

5. CONCLUSIONS

A method has been presented which enables the deduction of material data from a limited number of known characteristic values on the material stress-strain curve. The method is flexible and may be used for a wide range of materials, aluminium alloys and many others, having tensile or compressive stress-strain curves of the general form of expression (3) in the range of strains under consideration. This general form is one having a finite linear range (which may be quite short, as in the case of some magnesium alloys) followed by a smooth curve in the post-linear range.

The form of presentation chosen in order to achieve a high degree of accuracy and flexibility of application is the nomogram. Although nomograms have disadvantages, the type selected is straightforward in operation and a few minutes familiarisation with the method of use is all that is necessary to enable the user to extract data appropriate to a wide range of materials from whatever characteristic values may be available for those materials.

The accuracy of the method is high and of comparable order to that with which specification values are usually recorded and to that which can be achieved in obtaining material data from known stress-strain curves by geometrical means. The accuracy of the results depends upon how near the part of the stress-strain curve for which data is obtained from the nomograms corresponds to the part of the curve represented by the range f_R to f_R'. The highest accuracy is achieved when the stress values, appropriate to the data extracted, lie between f_R and f_R'. To prevent unwitting extrapolation beyond this range it has been found convenient to specify $f_R > f_R'$ and to plot the nomograms only up to values of $f/f_R = 1{\cdot}0$.

By keeping the presentation in quite general terms it is possible to select, from whatever characteristic values may be available, those which will yield the highest accuracy in the results. Further, if the range of characteristic values available is limited it is still possible to obtain results which are sufficiently accurate for most practical purposes.

ACKNOWLEDGMENT

The authors wish to acknowledge the advice given by the Society's Structures Committee during the progress of this work and the assistance of Miss E. Parrish in the preparation of the diagrams.

REFERENCES

1. Royal Aeronautical Society. Structures Data Sheets 00.02.01, 02 and 03. June 1948 and October 1951.
2. NICHOLLS, A. C. (1954). Empirical Formulae for the Determination of Stress Curves. *Journal of the Royal Aeronautical Society*, October 1954.
3. RAMBERG, W. and OSGOOD, W. R. (1943). Description of Stress-Strain Curves by Three Parameters. N.A.C.A. T.N.902, April 1943.
4. BARRETT, ANTHONY J. (1953). The Bending of Some Common Beam Sections into the Plastic Range. *Journal of the Royal Aeronautical Society*, February 1953.
5. DURHAM, R. J. (1953). Stress-Strain Curves for Some Noral Wrought Alloys. Aluminium Laboratories Research Bulletin No. 2. June 1953.
6. LEGG, K. L. C. and WRIGHT, J. H. (1954). Note on Proposed Revised R.Ae.S. Data Sheets for Stress-Strain Curves. Short Bros. & Harland Note S.D. No. 2, September 1954.
7. BARRETT, ANTHONY J. (1953). Unsymmetrical Bending and Bending Combined with Axial Loading of a Beam of Rectangular Cross Section into the Plastic Range. *Journal of the Royal Aeronautical Society*, August 1953.

THE LIBRARY

Reviews

MASSBALANCING OF AIRCRAFT CONTROL SURFACES. *H. Templeton. Volume IV of a Series of Aeronautical Monographs published under the authority of the Royal Aeronautical Society. Chapman & Hall, London, 1954. 241 pp. 39 figures. 35s.*

The phenomenon of aeroplane flutter, first recognised and documented in 1916, has lost none of its inherent danger with the passing of the years; indeed, far more attention has now to be paid to the treatment of flutter problems than has ever been the case before. Despite this, the rapid developments of aircraft in the past few years have continued to bring in their train more flutter incidents or accidents, and these have mostly involved control surfaces and tabs.

As a result, there has been a large amount of intensive work on the prevention of control surface and tab flutter, some form of massbalance being the normal curative or preventive measure employed. Concomitantly, there has been a rising tide of technical papers in this field, and a pressing need has arisen for a digest in the form of a textbook or monograph.

The volume under review is therefore very timely and welcome, particularly as its author is in charge of flutter investigations at the Royal Aircraft Establishment, and is, in consequence, in close touch with all current developments. The volume contains some 250 pages and is divided into three Parts: Part I states the basic principles of massbalancing, Part II gives a record of the past applications of massbalancing, including design criteria, practical procedures, and discussions of systems which have been employed, and Part III looks to future developments and notes some methods of flutter prevention alternative to massbalance. There are also an Introduction and some Appendices. The author has, incidentally, proposed a consistent terminology for the subject; it is to be hoped that this will be universally adopted.

The reviewer found the book convincing, authoritative, and helpful; it is clearly written and well planned. The style is perhaps a little frigid, and loses something of the magic and mystery of the subject; but this is a small fault —perhaps, indeed, a virtue—in a book which has as its object a lucid, simple, and factual exposition of a difficult subject. Flutter investigations are essentially mathematical in character, involving sets of linear differential equations and depending heavily on the theory of determinants and the complex variable. No book on the subject could be criticised for being heavily mathematical; but the volume under review can be praised for using a minimum of mathematics, and for giving many helpful diagrams. It can be heartily recommended.—A.R.C.

FURTHER OUTLOOK. *F. H. Ludlam and R. S. Scorer. With an Introduction by Sir David Brunt. 174 pp., with 13 plates and 25 figures. Allan Wingate, London, 1954. 15s.*

There are many "popular" books on meteorology—some are now reckoned among the classics of the science and others are best forgotten. It should be said at once that the present volume, written by two of the younger members of the staff of the Department of Meteorology of Imperial College, is among the better examples. It is a series of highly individual essays written, for the most part, with the assurance that comes only from first-hand acquaintance with the subject. As a survey this book deserves to be read, not only by professional meteorologists but by all who are interested in the atmosphere and its problems.

The opening is conventional; an account of weather and its relation to the familiar pressure patterns. Much space is given to the process of rain formation, which abounds in problems not yet fully solved by the meteorologist. This is followed by a chapter on turbulence. It is a severe test for anyone to write a condensed account of this difficult topic for the general reader, and it is not altogether surprising that the text occasionally falters. The definitions of diffusion ("a process whereby particles or molecules that are contained in a fluid are transferred from one place to another without any bulk transfer of the fluid"—surely, for *bulk* one must read *net*?) and of turbulence ("that part of the motion which causes diffusion") are examples of attempts at condensation that defeat their purpose. However, in the chapter that follows, which deals mainly with convection and its consequences for soaring flight, the authors are on ground which they may rightly call their own, and this is reflected in the vigour and clarity of the writing. Here the reader will find some very interesting observations on natural flight, and it is doubtful if the meteorology of gliding has ever been better discussed.

The rest of the book is largely concerned with forecasting and the possibilities of weather control. Time-honoured methods of synoptic forecasting are described as an "art"—a description with which few would quarrel—and this is followed by a somewhat diffuse and sketchy account of the impact of high-speed computing on the problem. Then comes a fairly detailed analysis of "rain-making," the process of seeding suitable clouds with pellets of "dry-ice" or particles of silver iodide. This is a good piece of objective writing, much needed in a subject with such a chequered history. No responsible scientist would deny that in this way it may be possible to cause changes in cloud structure and perhaps even to stimulate precipitation, but this is far removed from the blind acceptance of claims that such operations will pay worthwhile dividends. The lucid account given here may go some way to convince the general reader that the professional meteorologist has good reasons for exercising caution in his acceptance of such claims. Finally, in a chapter entitled "Uncertainties" the authors discourse on a variety of topics that interest meteorologists but may not be as well known outside the profession.

The impression left on the reviewer is that of a lively but somewhat uneven work. At times it is very good, and even in the less inspired chapters—chiefly those on turbulence and numerical forecasting—it is never dull. The style, although at times a little rough, is always clear, but the work would have lost nothing in emphasis and perhaps had greater appeal if the historical side had been brought out more. (It is unusual, to say the least, to devote so much space to clouds and rain without mentioning Bergeron, or to discuss depressions without bringing in the name of Bjerknes, to give only two examples. But such idiosyncrasies are minor flaws in a book as fresh and as interesting as this.)

The plates, mainly reproductions of cloud photographs by Mr. Ludlam, are all very good, but the design on the dust cover is an artistic error that fortunately bears little relation to the general sobriety of the text.—O. G. SUTTON.

presented. The experimental results are presented mainly in the form of flight ratings for stability, control, and general flight behaviour. Calculations of period and damping and of the response to rolling and yawing disturbances are also presented.—(1.8.1).

Effect of horizontal-tail span and vertical location on the aerodynamic characteristics of an unswept tail assembly in sideslip. D. R. Riley. N.A.C.A. Report 1171 (1954).

Wind-tunnel results on the effect of horizontal-tail span and vertical location of the horizontal tail relative to the vertical tail on the aerodynamic characteristics of an unswept vertical-tail assembly in sideslip are presented. By applying the discrete-horseshoe-vortex method used for wings to the problem of intersecting surfaces, theoretical span loadings were obtained for each of the configurations tested.—(1.8.1.2).

Aerodynamic forces, moments, and stability derivatives for slender bodies of general cross section. A. H. Sacks. N.A.C.A. Technical Note 3283 (*November* 1954).

Formulae are developed for forces and moments in terms of the body shape and motions, and for stability derivatives in terms of the mapping functions of the cross sections. Relationships are found among the various derivatives, and calculations are made for several configurations. The influence of the squared terms in the pressure relation is demonstrated, and the use of the apparent mass concept is discussed in detail.—(1.8.0.2).

Wings and Aerofoils

See also Compressible Flow

*On the theory of oscillating airfoils of finite span in subsonic flow. W. Eckhaus. N.L.L. Report F.*153 (*published* 1954).

In this report a survey is given of the present state of theories, dealing with the oscillating aerofoil of finite span in incompressible and in compressible subsonic flow. The accuracy and the applicability of these theories is investigated while, in some cases, more rigorous derivations are presented, in order to deepen the insight into the problem.—(1.10.1.2).

*The induced drag due to disturbances in the lift distribution. W. Eckhaus. N.L.L. Report F.*154 (*published* 1954).

An approximate method is presented by which the increase in the induced drag caused by a disturbance in the lift distribution, for some frequently occurring types of disturbances, can rapidly be calculated from graphs. By means of a worked example the good accuracy of the method is illustrated.—(1.10.1.2).

Helicopter Aerodynamics

Preliminary results from flow-field measurements around single and tandem rotors in the Langley full-scale tunnel. H. H. Heyson. N.A.C.A. Technical Note 3242 (*November* 1954).

Measurements of the flow angles and velocities near lifting helicopter rotors, both single and tandem, at a tip-speed ratio of 0·15 are presented and compared with those of theory. The comparison indicates that the theory is sufficiently accurate for use in preliminary design calculations. The flow behind a rotor is shown to be very much like the flow behind a wing.—(1.11.3).

Testing and Instruments

See also Compressible Flow

The theoretical interference velocity on the axis of a two-dimensional wind tunnel with slotted walls. R. C. Tomlinson. A.R.C. Current Paper 181 (*August* 1950, *published* 1954).

A calculation is made of the interference velocity on the axis in the flow of an incompressible fluid past a line doublet in a two-dimensional slotted-wall tunnel, *i.e.* a rectangular tunnel whose shorter sides are slotted in the direction of the flow. The method of analysis is basically the same as that used for cylindrical tunnels by Wright and Ward.—(1.12.1.1).

The efficiency of high-speed wind tunnels of the induction type. A. E. Knowler and D. W. Holder. R. & M. 2448 (*December* 1948, *published* 1954). —(1.12.1.3).

A method of calibrating airspeed installations of airplanes at transonic and supersonic speeds by the use of accelerometer and attitude-angle measurements. J. A. Zalovcik, L. J. Lina and J. P. Trant. N.A.C.A. Report 1145 (1953).

A method is described for calibrating air speed installations on aeroplanes at transonic and supersonic speeds in which use is made of normal and longitudinal accelerations and attitude angle as measured by instruments carried within the aeroplane. An air speed calibration of the pitot-static installation on a jet fighter aeroplane is presented as an experimental check on the accuracy of the method.—(1.12.2 × 13.3).

Liquefaction of air in the Langley 11*-inch hypersonic tunnel, C. H. McLellan and T. W. Williams. N.A.C.A. Technical Note* 3302 (*October* 1954).

Pressure and scattered-light measurements were made in the Langley 11-inch hypersonic tunnel to determine the effect of stagnation temperature on the flow in two Mach number 7 nozzles and to determine the nature of the condensation process occurring at low stagnation temperatures. Liquefaction of the air occurred very close to the saturation point without a condensation shock. The results from varying the water vapour and carbon-dioxide content could not be correlated with Max Volmer's condensation theory.—(1.12.1.3).

AEROELASTICITY

See also Aerodynamics: Loads

An exploratory investigation of some types of aeroelastic instability of open and closed bodies of revolution mounted on slender struts. S. A. Clevenson, E. Widmayer and F. W. Diederich. N.A.C.A. Technical Note 3308 (*November* 1954).

The aeroelastic instability of rigid open and closed bodies of revolution mounted on thin, flexible struts has been investigated experimentally at low speeds. Three types of instability were observed—coupled flutter, divergence, and an uncoupled oscillatory instability which consists in continuous or intermittent small-amplitude yawing oscillations.—(2).

FLIGHT TESTING

A note on the development of sensitive pressure operated water contacts for use on seaplanes. R. Parker. A.R.C. Current Paper 176 (*July* 1952, *published* 1954).

A pressure operated water contact has been developed, suitable for indicating the instants of take-off and touch-down for a seaplane hull. Flight tests have shown that the instrument is accurate in operation and sufficiently robust for normal flight test use.—(13.3).

HYDRODYNAMICS

A survey of scale effects on the hydrodynamic testing of seaplane models. R. Parker. A.R.C. Current Paper 179 (*September* 1953, *published* 1954).

A general survey is made of all the factors where true dynamic similarity cannot be achieved in model tests of seaplane hulls; the likely effects on test results are discussed with reference to towing tank models and medium size research aircraft.—(17.2).

INSTRUMENTS AND EQUIPMENT

Description and preliminary flight investigation of an instrument for detecting subnormal acceleration during take-off. G. J. Morris and L. J. Lina. N.A.C.A. Technical Note 3252 (*November* 1954).

An instrument actuated by longitudinal acceleration and impact pressure has been proposed which would give a quick and easily recognisable quantitative indication of loss in aeroplane acceleration during take-off. A preliminary evaluation from flight tests of a simplified prototype instrument mounted in a jet trainer has been made. The instrument was found to be satisfactory and the response of the indicator to simulated partial power loss was rapid.—(18).

4. ACCURACY

The accuracy of the method is now considered. It will be remembered that the data is required for use in three ways, as a stress-strain expression, as the first differential of the stress-strain curve (for tangent modulus applications, etc.) and in the integrated form for areas and first moments of areas of the stress-strain curve. The last of these applications has been considered in Refs. 4 and 7. It is sufficient to note here, in respect to these integrative processes, that if the expressions give a satisfactory representation of stress versus strain, the accuracy of integration will be of a high order.

The following examination may be made of the proximity to which expression (3) represents actual material stress-strain curves.

The expression has been made to represent the initial slope of the stress-strain curve and to pass through two known points on the curve, $[f_R, (\varepsilon_R + f_R/E)]$ and $[f_R', (\varepsilon_R' + f_R'/E)]$. If a third known point on the actual curve is $[f_R'', (\varepsilon_R'' + f_R''/E)]$ and the mathematical curve of expression (3) gives a stress corresponding to a non-proportional strain ε_R'' of f_R'' $(1+\Delta)$ then

$$\log(f_R/f_R') = \frac{\log(\varepsilon_R/\varepsilon_R')}{\log(\varepsilon_R''/\varepsilon_R)} \{\log(f_R''/f_R) + \log(1+\Delta)\}.$$

By use of this expression it is possible to find how near the mathematical curve passes to a third proof stress value when it is made to pass through two known proof stress values.

126 sets of f_5, f_2 and f_1 were used, taken from Ref. 5. These values are appropriate to a very wide range of typical tensile and compressive stress-strain curves for aluminium alloys. In Table I the number of cases in which the mathematical curve gave a value of the third of these proof stresses to within 2 per cent. is shown. There are two points of note. Firstly, 11 of the 126 sets of values showed inflexions and did not correspond to stress-strain curves of the same form as equation (2). However, all 126 sets are considered and the results of Table I reflect the accuracy of the method when applied without prior selection of the data. Secondly, the accuracy is seen to be greatest when the data extracted corresponds to points on the stress-strain curve between points of coincidence of the actual and mathematical stress-strain curves. This is a result typical of any such process; interpolation invariably being more accurate than extrapolation. Bearing in mind that a high degree of accuracy is obtained when stress values, appropriate to the data extracted, lie between f_R and f_R' and that this decreases the further these stress values deviate from this range, the accuracy of the method in respect to the representation of stress and strain is satisfactory.

TABLE I

f_R	f_R'	f_R''	*Number of cases in which* $0{\cdot}02 > \Delta > -0{\cdot}02$
f_5	f_2	f_1	106
f_5	f_1	f_2	122
f_2	f_1	f_5	92

The accuracy of the method when applied to the evaluation of data involving E_t has been checked in the following way.

From actual stress-strain curves values of E_t were obtained in the conventional manner at various stress levels, and values of f/E_t calculated. These values of f/E_t and the known values of proof stresses and Young's moduli were used in the nomogram of Fig. 5 to evaluate values for f for comparison with the stress values taken from the actual curve. Various pairs of proof stress values were used as the characteristics f_R and f_R', the results being as shown in Table II. Similar checks have been made independently in Ref. 6 where the method is applied to a number of aluminium alloys, titanium alloys and a magnesium alloy. In all cases when the data

TABLE II

Material Properties				*By measurement from stress-strain curve*		*Nomogram value of f for measured value of* f/E_t		
E	f_1	f_2	f_5	f	f/E_t	$f_R=f_2 \mid f_R'=f_1$	$f_R=f_5 \mid f_R'=f_1$	$f_R=f_5 \mid f_R'=f_2$
$9{\cdot}6\times10^6$	13·2	13·7	14·8	12·4	0·0062	12·3	12·4	12·1
				13·2	0·0150	13·1	13·1	13·1
				13·7	0·0326	13·6	13·9	14·0
				14·1	0·0411	—	14·2	14·2
$10{\cdot}5\times10^6$	38·1	38·9	40·2	36·5	0·011	36·4	37·3	37·3
				38·1	0·021	37·5	37·9	38·3
				39·0	0·065	39·0	39·0	38·9
				39·5	0·113	—	39·6	39·7
$10{\cdot}4\times10^6$	66·0	67·9	70·6	63·0	0·0121	61·8	62·5	60·7
				66·0	0·0287	65·7	65·7	64·2
				67·9	0·0566	67·9	67·9	66·7
				69·0	0·0767	—	69·2	67·8
$10{\cdot}7\times10^6$	87·6	90·3	92·8	83·5	0·0139	83·0	84·9	84·0
				87·6	0·0258	86·7	87·0	86·8
				90·3	0·0602	91·2	89·7	89·2
				91·7	0·0834	—	90·9	90·5

All units of stress are lb./in.$^2\times10^{-3}$.

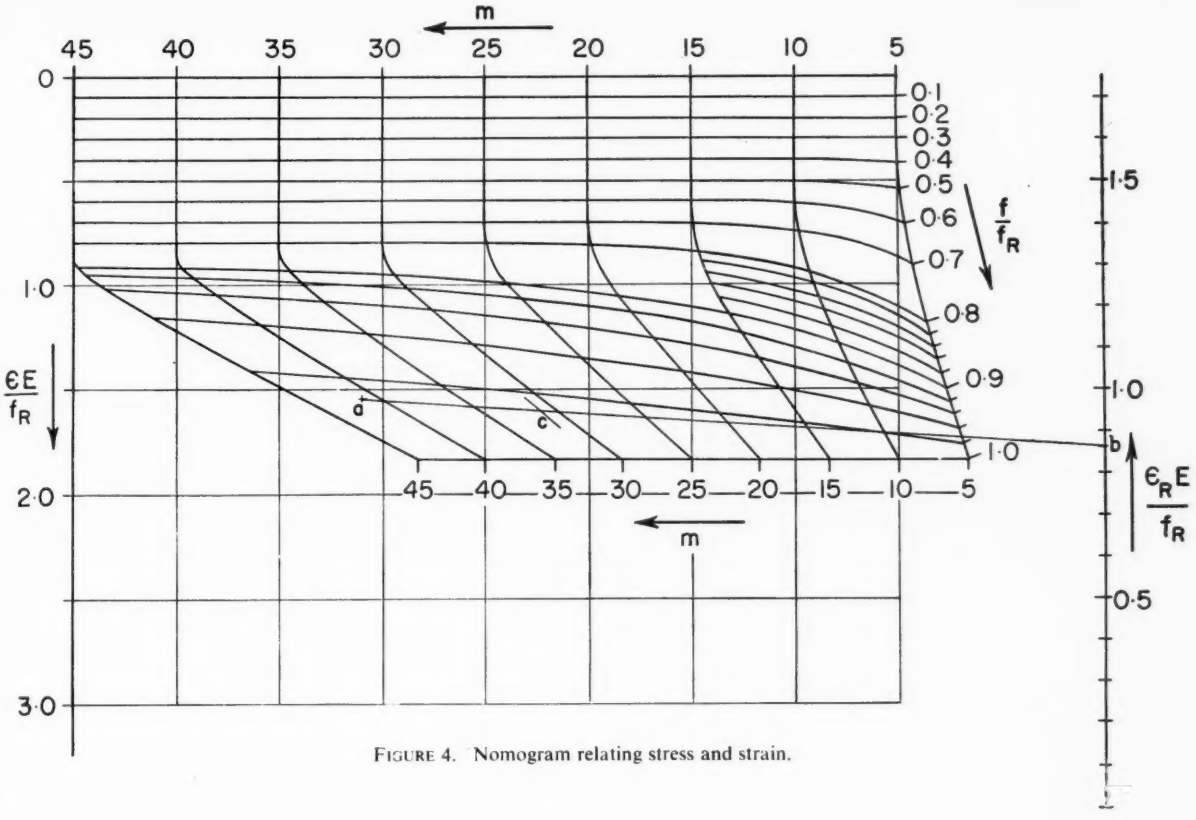


FIGURE 4. Nomogram relating stress and strain.

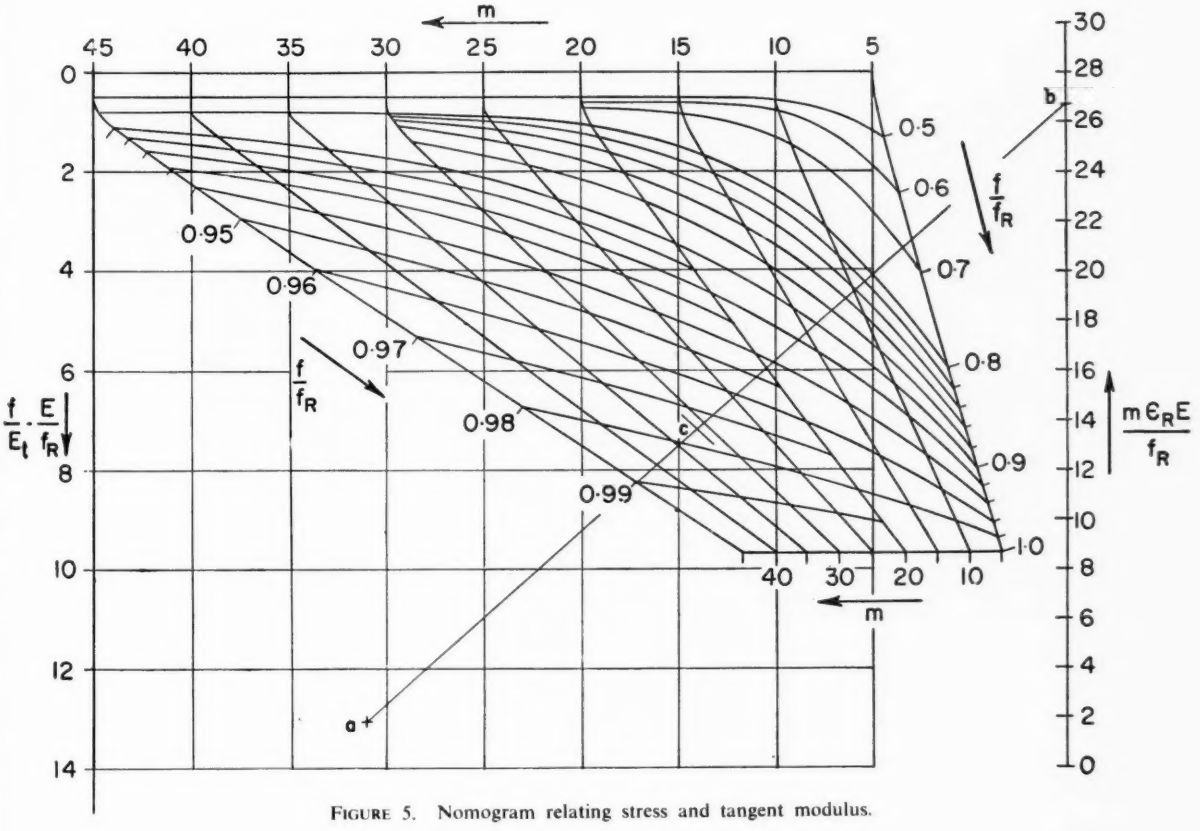


FIGURE 5. Nomogram relating stress and tangent modulus.

extracted lay in the range f_R to f_R' the error was less than about 1 per cent. and when the data extracted lay outside this range the error was usually less than 2 per cent. The worst error recorded was 6 per cent. in a case where the data extracted was appropriate to a stress value only slightly beyond the limit of proportionality of the material, the reference stresses used being f_5 and f_2. Since these errors are of only the same order as those involved in obtaining values of E_t by geometrical means the accuracy of the proposed method would seem to be satisfactory.

5. CONCLUSIONS

A method has been presented which enables the deduction of material data from a limited number of known characteristic values on the material stress-strain curve. The method is flexible and may be used for a wide range of materials, aluminium alloys and many others, having tensile or compressive stress-strain curves of the general form of expression (3) in the range of strains under consideration. This general form is one having a finite linear range (which may be quite short, as in the case of some magnesium alloys) followed by a smooth curve in the post-linear range.

The form of presentation chosen in order to achieve a high degree of accuracy and flexibility of application is the nomogram. Although nomograms have disadvantages, the type selected is straightforward in operation and a few minutes familiarisation with the method of use is all that is necessary to enable the user to extract data appropriate to a wide range of materials from whatever characteristic values may be available for those materials.

The accuracy of the method is high and of comparable order to that with which specification values are usually recorded and to that which can be achieved in obtaining material data from known stress-strain curves by geometrical means. The accuracy of the results depends upon how near the part of the stress-strain curve for which data is obtained from the nomograms corresponds to the part of the curve represented by the range f_R to f_R'. The highest accuracy is achieved when the stress values, appropriate to the data extracted, lie between f_R and f_R'. To prevent unwitting extrapolation beyond this range it has been found convenient to specify $f_R > f_R'$ and to plot the nomograms only up to values of $f/f_R = 1{\cdot}0$.

By keeping the presentation in quite general terms it is possible to select, from whatever characteristic values may be available, those which will yield the highest accuracy in the results. Further, if the range of characteristic values available is limited it is still possible to obtain results which are sufficiently accurate for most practical purposes.

ACKNOWLEDGMENT

The authors wish to acknowledge the advice given by the Society's Structures Committee during the progress of this work and the assistance of Miss E. Parrish in the preparation of the diagrams.

REFERENCES

1. Royal Aeronautical Society. Structures Data Sheets 00.02.01, 02 and 03. June 1948 and October 1951.
2. NICHOLLS, A. C. (1954). Empirical Formulae for the Determination of Stress Curves. *Journal of the Royal Aeronautical Society*, October 1954.
3. RAMBERG, W. and OSGOOD, W. R. (1943). Description of Stress-Strain Curves by Three Parameters. N.A.C.A. T.N.902, April 1943.
4. BARRETT, ANTHONY J. (1953). The Bending of Some Common Beam Sections into the Plastic Range. *Journal of the Royal Aeronautical Society*, February 1953.
5. DURHAM, R. J. (1953). Stress-Strain Curves for Some Noral Wrought Alloys. Aluminium Laboratories Research Bulletin No. 2. June 1953.
6. LEGG, K. L. C. and WRIGHT, J. H. (1954). Note on Proposed Revised R.Ae.S. Data Sheets for Stress-Strain Curves. Short Bros. & Harland Note S.D. No. 2, September 1954.
7. BARRETT, ANTHONY J. (1953). Unsymmetrical Bending and Bending Combined with Axial Loading of a Beam of Rectangular Cross Section into the Plastic Range. *Journal of the Royal Aeronautical Society*, August 1953.

THE LIBRARY

Reviews

MASSBALANCING OF AIRCRAFT CONTROL SURFACES. *H. Templeton. Volume IV of a Series of Aeronautical Monographs published under the authority of the Royal Aeronautical Society. Chapman & Hall, London, 1954. 241 pp. 39 figures. 35s.*

The phenomenon of aeroplane flutter, first recognised and documented in 1916, has lost none of its inherent danger with the passing of the years; indeed, far more attention has now to be paid to the treatment of flutter problems than has ever been the case before. Despite this, the rapid developments of aircraft in the past few years have continued to bring in their train more flutter incidents or accidents, and these have mostly involved control surfaces and tabs.

As a result, there has been a large amount of intensive work on the prevention of control surface and tab flutter, some form of massbalance being the normal curative or preventive measure employed. Concomitantly, there has been a rising tide of technical papers in this field, and a pressing need has arisen for a digest in the form of a textbook or monograph.

The volume under review is therefore very timely and welcome, particularly as its author is in charge of flutter investigations at the Royal Aircraft Establishment, and is, in consequence, in close touch with all current developments. The volume contains some 250 pages and is divided into three Parts: Part I states the basic principles of massbalancing, Part II gives a record of the past applications of massbalancing, including design criteria, practical procedures, and discussions of systems which have been employed, and Part III looks to future developments and notes some methods of flutter prevention alternative to massbalance. There are also an Introduction and some Appendices. The author has, incidentally, proposed a consistent terminology for the subject; it is to be hoped that this will be universally adopted.

The reviewer found the book convincing, authoritative, and helpful; it is clearly written and well planned. The style is perhaps a little frigid, and loses something of the magic and mystery of the subject; but this is a small fault —perhaps, indeed, a virtue—in a book which has as its object a lucid, simple, and factual exposition of a difficult subject. Flutter investigations are essentially mathematical in character, involving sets of linear differential equations and depending heavily on the theory of determinants and the complex variable. No book on the subject could be criticised for being heavily mathematical; but the volume under review can be praised for using a minimum of mathematics, and for giving many helpful diagrams. It can be heartily recommended.—A.R.C.

FURTHER OUTLOOK. *F. H. Ludlam and R. S. Scorer. With an Introduction by Sir David Brunt. 174 pp., with 13 plates and 25 figures. Allan Wingate, London, 1954. 15s.*

There are many " popular " books on meteorology—some are now reckoned among the classics of the science and others are best forgotten. It should be said at once that the present volume, written by two of the younger members of the staff of the Department of Meteorology of Imperial College, is among the better examples. It is a series of highly individual essays written, for the most part, with the assurance that comes only from first-hand acquaintance with the subject. As a survey this book deserves to be read, not only by professional meteorologists but by all who are interested in the atmosphere and its problems.

The opening is conventional; an account of weather and its relation to the familiar pressure patterns. Much space is given to the process of rain formation, which abounds in problems not yet fully solved by the meteorologist. This is followed by a chapter on turbulence. It is a severe test for anyone to write a condensed account of this difficult topic for the general reader, and it is not altogether surprising that the text occasionally falters. The definitions of diffusion (" a process whereby particles or molecules that are contained in a fluid are transferred from one place to another without any bulk transfer of the fluid "—surely, for *bulk* one must read *net*?) and of turbulence (" that part of the motion which causes diffusion ") are examples of attempts at condensation that defeat their purpose. However, in the chapter that follows, which deals mainly with convection and its consequences for soaring flight, the authors are on ground which they may rightly call their own, and this is reflected in the vigour and clarity of the writing. Here the reader will find some very interesting observations on natural flight, and it is doubtful if the meteorology of gliding has ever been better discussed.

The rest of the book is largely concerned with forecasting and the possibilities of weather control. Time-honoured methods of synoptic forecasting are described as an " art "—a description with which few would quarrel—and this is followed by a somewhat diffuse and sketchy account of the impact of high-speed computing on the problem. Then comes a fairly detailed analysis of " rain-making," the process of seeding suitable clouds with pellets of " dry-ice " or particles of silver iodide. This is a good piece of objective writing, much needed in a subject with such a chequered history. No responsible scientist would deny that in this way it may be possible to cause changes in cloud structure and perhaps even to stimulate precipitation, but this is far removed from the blind acceptance of claims that such operations will pay worthwhile dividends. The lucid account given here may go some way to convince the general reader that the professional meteorologist has good reasons for exercising caution in his acceptance of such claims. Finally, in a chapter entitled " Uncertainties " the authors discourse on a variety of topics that interest meteorologists but may not be as well known outside the profession.

The impression left on the reviewer is that of a lively but somewhat uneven work. At times it is very good, and even in the less inspired chapters—chiefly those on turbulence and numerical forecasting—it is never dull. The style, although at times a little rough, is always clear, but the work would have lost nothing in emphasis and perhaps had greater appeal if the historical side had been brought out more. (It is unusual, to say the least, to devote so much space to clouds and rain without mentioning Bergeron, or to discuss depressions without bringing in the name of Bjerknes, to give only two examples. But such idiosyncrasies are minor flaws in a book as fresh and as interesting as this.)

The plates, mainly reproductions of cloud photographs by Mr. Ludlam, are all very good, but the design on the dust cover is an artistic error that fortunately bears little relation to the general sobriety of the text.—O. G. SUTTON.

LIMITATION OF LIABILITIES IN INTERNATIONAL AIR LAW. *H. Drion. Martinus Nijhoff, The Hague, 1954. 389 pp. 24.50 guilders.*

This is a book for students and experts, rather than for general practitioners, carriers and operators of aircraft. The author is a brilliant young Dutch lawyer, who has had the advantage of having attended, as a Delegate, Meetings of the Legal Committee of I.C.A.O. dealing with the proposed revision of the Warsaw Convention and with the Rome Convention of 1952. He is also a legal adviser to K.L.M. It is believed that the book constitutes the treatise required in connection with his application for a Doctorate in Law.

The author has chosen the English language for reasons explained in the Preface, and the English is admirable. It is a scholarly book, and worthy of study by all those who, as lawyers, have to deal with claims arising from air carriage and from damage caused to third parties on the surface. The sixty-nine pages devoted to the subject of "wilful misconduct," and the historical explanations of some of the peculiarities in the Warsaw Convention, are of particular interest; and the subjects are dealt with in a practical manner, including some humorous comments.

The arguments for and against various principles are well explained, although in one or two cases the conclusions reached might not receive universal approval; for instance, the statement that unification of the law as a ground for limitation of liability should be rejected, and the construction placed upon the phrase "value at delivery" (intérêt à la livraison). These latter, however, are minor points. Much more important is the admirable manner in which the author draws attention to all the main features of the problems which give rise to difficulties created by the fact that differing principles are applied in different countries, and widely differing limits (if any) of liability for unlawful death; also the views expressed concerning "servants and agents" (préposés), the reasoning concerning Article 22 of the Warsaw Convention, the basis of calculating the limits of liability in the event of partial loss of cargo or baggage and the complications involved in calculating the limits under the Rome Convention of 1952. As the latter Convention has not yet been ratified by any State, and there are no precedents, as authorities, the author's views on this are particularly valuable, although some of the problems to which he calls attention may be resolved if the proposed Convention dealing with aerial collisions, recently drafted by the Legal Committee of I.C.A.O., is ratified, especially the problems involved in recourse claims.

The book includes a modern list of cases decided in fifteen countries, a list of books and articles dealing with the matters treated and the English texts of the Warsaw Convention and the Rome Convention of 1952; together with a good Index.

For the student and expert it is a book of great interest and real value.—K. M. BEAUMONT.

CHESHIRE V.C. *Russell Braddon. Evans Brothers, London, 1954. 217 pp. Illustrated. 12s. 6d.*

During the Second World War the daring exploits and devotion to duty of Group Captain Leonard Cheshire, V.C., D.S.O., D.F.C., captured the imagination of a grateful country, yet his fame may well be remembered more for the devotion of his physical and material resources to the care of the lonely and the sick.

What manner of man is this Oxford graduate ex-bomber pilot whose outlook altered completely after witnessing the explosion of the Nagasaki atom bomb and whose vocation and faith similarly changed with the illness and death of an ex-L.A.C.? Perhaps Russell Braddon is a little complacent that he has succeeded in making the revelation, for though he covers the factual story of Leonard Cheshire's entire life, and quotes verbatim many scraps of conversation from his contemporary interviews, the essential character of his subject remains obscure. Neither in the portrayal of the fighting man at war, whose citation described him as having "a reputation second to none in Bomber Command," nor in the briefer sketch of the man of peace fighting for quite different ideals is it possible to perceive the vital spark which galvanised him so often to attempt the impossible and succeed. Yet the brilliance and energy Cheshire so persistently applied to the pursuits of war he still devotes to a crusade which is maintained despite his own desperate illness and frequent financial crises. With such evidence it should have been possible to treat this biography more imaginatively, expressing the subject's character through the manifestation of action.

Nevertheless, the author presents his pen-portrait honestly if admiringly, and generally very readily despite the jangle of phrases having the calibre of: "as the screaming plane straightened out of her dive Cheshire, and Kelly beside him, became dizzy with the relentless pressure of gravity." One suspects that although Russell Braddon has the sympathy of a novelist he knows much less of the outlook of a pilot.—HARALD PENROSE.

DEFINITIONS FOR USE IN MECHANICAL ENGINEERING. *B.S. 2517. British Standards Institution, London, 1954. 36 pp. Diagrams. 6s.*

The short title of this standard is confusing and one must consider the whole thing—"Definitions relating to construction, drawing practice, size and tolerance, limits and fits screw threads, surface texture and gauges" which *is* really quite a good review. It is, nevertheless, amazing that such a long time should have elapsed before the need was felt for such a standard when one considers the age of the Glossary of Aeronautical Terms.

Additions to the Library

Bennett, J. A. and G. W. Quick. MECHANICAL FAILURES OF METALS IN SERVICE. National Bureau Standards Circular 550. U.S.G.P.O. 1954.

Biezeno, C. B. and R. Grammel. ENGINEERING DYNAMICS VOL. I. THEORY OF ELASTICITY. Blackie. 1955.

D.S.I.R. REPORT OF COMMITTEE ON VAPORIZING LIQUID EXTINGUISHING AGENTS (FIRE RESEARCH TECHNICAL PAPER NO. 2). H.M.S.O. 1954.

Forsythe, W. E. SMITHSONIAN PHYSICAL TABLES. 9th Revised Edition. Smithsonian Inst. 1954.

Institute of the Aeronautical Sciences. PROCEEDINGS: NATIONAL TURBINE POWERED AIR TRANSPORTATION MEETINGS. I.A.S. 1954.

Matthews, *Sir* Bryan, *et al.* A DISCUSSION ON THE PHYSIOLOGY OF MAN AT HIGH ALTITUDES. Procs. B. Royal Society No. 910. Royal Society. 1954.

Northern Aluminium Co. Ltd. PROPERTIES OF NORAL ALLOYS. 1954.

Reid, D. G. BALSA WOOD AS AN END-GRAIN CORE MATERIAL IN SANDWICH CONSTRUCTION. (Pamphlet-photostat) Chance-Vought.

Saville, W. S. RECENT DEVELOPMENTS IN SANDWICH CONSTRUCTION. (Preprint S.A.E.) 1951.

Reports

AERODYNAMICS

Boundary Layer

*A one-parameter method for the calculation of laminar compressible boundary-layer flow with a pressure gradient. J. A. Zaat. N.L.L. Report F.*141. (*November* 1953).

Based on the momentum equation of von Kármán and the integrated heat equation, suppositions are made for the analysis of the velocity and temperature profiles in laminar compressible boundary layer flow. The method is set up by means of the asymptotic behaviour of the boundary layer profiles and takes into account as many boundary conditions at the wall as possible. In connection with these boundary conditions the flow with and without heat transfer at the wall is dealt with.—(1.1.1.2).

Experimental determination of boundary-layer transition on a body of revolution at M=3·5. J. R. Jedlicka, M. E. Wilkins and A. Seiff. N.A.C.A. Technical Note 3342 (*October* 1954).

Boundary-layer-transition tests were made in free flight through still air on a small-scale fin-stabilised body of revolution of fineness ratio 30 at a Mach number of 3·5 and length Reynolds numbers of 12 and 24 million.—(1.1.2.4).

Compressible Flow

A method of computing subsonic and transonic plane flows. C. S. Sinnot. A.R.C. Current Paper 173 (*September* 1953, *published* 1954).

This paper presents a relaxation treatment of a simple but exact differential equation for compressible flow. The method has advantages over other numerical treatments of the same problem and because of the simplicity of the basic differential equation should be particularly suitable for high-speed computing machines.—(1.2.2 × 1.10.1.1).

The zero-lift drag of a slender body of revolution (N.A.C.A. RM-10 Research Model) as determined from tests in several wind tunnels and in flight at supersonic speeds. A. J. Evans. N.A.C.A. Report 1160 (1954).

Zero-lift drag data are given of an N.A.C.A. RM-10 slender body of revolution with and without stabilising fins attached. The results from several wind tunnels and in flight are compared. The results cover a Reynolds number range from about 1×10^6 to 40×10^6 for the wind-tunnel models and 12×10^6 to 140×10^6 for the flight models. The Mach numbers covered include 1·5 to 2·4 in the wind tunnels and 0·85 to 2·5 in flight.—(1.2.1 × 1.7 × 1.12.1).

Convection of a pattern of vorticity through a shock wave. H. S. Ribner. N.A.C.A. Report 1164 (1954).

An arbitrary weak spatial distribution of vorticity can be represented in terms of plane sinusoidal shear waves of all orientations and wave lengths (Fourier integral). The analysis treats the passage of a single representative weak shear wave through a plane shock and shows refraction and modification of the shear wave with simultaneous generation of an acoustically intense sound wave. Applications to turbulence and to noise in supersonic wind tunnels are indicated.—(1.2.3.2).

On the determination of certain basic types of supersonic flow fields. C. Ferrari. N.A.C.A. Technical Memorandum 1381 (*November* 1954).

A discussion is given of the application of Fourier series techniques to the problems of linearised supersonic flow. The formulation presented is an extension of the doublet type of "fundamental solution" to higher order types of singularity. The equations developed have application to wing theory but are primarily of importance in wing-body interaction problems. A specific example of a wing-body interference problem is discussed in light of the presented methods.—(1.2.3.1).

Viscosity corrections to cone probes in rarefied supersonic flow at a nominal Mach number of 4. *L. Talbot. N.A.C.A. Technical Note* 3219 (*November* 1954).

Viscosity correction data were obtained for a set of geometrically similar cone probes in supersonic rarefied air flow at a nominal Mach number of 4. Additional experiments were made to determine cone surface pressure distributions and the effects of variable orifice size on the measurement of cone surface pressure. Pressure distributions near the vertex were compared with the tangent-cone and linearised theories.—(1.2.3 × 1.12.5).

Arrangement of fusiform bodies to reduce the wave drag at supersonic speeds. M. D. Friedman and D. Cohen. N.A.C.A. Technical Note 3345 (*November* 1954).

Using linearised slender-body theory and reverse-flow theorems, the wave drag of a system of fusiform bodies at zero angle of attack and supersonic speeds is studied to determine the effect of varying the relative location of the component parts.—(1.2.3).

Fluid Dynamics

Subsonic edges in thin-wing and slender-body theory. M. D. Van Dyke. N.A.C.A. Technical Note 3343 (*November* 1954).

A simple technique is presented for correcting the singularities predicted by thin-wing and slender-body theory at subsonic edges. Thus, Lighthill's rule for speeds on round-nosed aerofoils in incompressible flow is extended to higher approximations, compressible flow, three-dimensional wings, sharp edges, and slender bodies of revolution.—(1.4.1).

Internal Flow

The effect of inlet conditions on the flow in annular diffusers. I. H. Johnston. A.R.C. Current Paper 178 (*January* 1953, *published* 1954).

Tests have been carried out on annular diffusers having a common area ratio of 3·19 and varying in divergence angle from 6·5° to 15°. The performance of each diffuser has been measured for a variety of inlet velocity distributions and the effect of axially splitting the flow in the diffusers has been investigated.—(1.5.1.1).

A visualization study of secondary flows in cascades. H. Z. Herzig et al. N.A.C.A. Report 1163 (1954).

Flow-visualisation techniques are employed to ascertain the streamline patterns of the non-potential, secondary flows in the boundary layers of cascades, thereby providing a basis for more extended analyses in turbo-machines.—(1.5.4).

Loads

*Tables of aerodynamic coefficients for an oscillating wing-flap system in a subsonic compressible flow. N.L.L. Report F.*151 (*May* 1954).

This report contains the numerical results for the aerodynamic coefficients of an oscillating wing-flap system, where the flap hinge axis coincides with the flap nose. The complete set of 9 complex coefficients is given for the Mach numbers $\beta = 0{\cdot}35$, 0·5, 0·6, 0·7, 0·8. The ratio of flap to wind chord is 0·1, 0·2, 0·3. Exact calculations have been made for 9 or 10 values of the reduced frequency ω in case of the wing coefficients and for 7 or 8 ω-values in case of the flap coefficients. Interpolated values are presented for $\omega = 0$ (0·02), 0·90 if $\beta = 0{\cdot}8$ and for $\omega = 0$ (0·02), 1 for all other β-values.—(1.6.3 × 2.0).

Stability and Control

The effects on dynamic lateral stability and control of large artificial variations in the rotary stability derivatives. R. O. Schade and J. L. Hassell. N.A.C.A. Report 1151 (1953).

The results of an experimental and theoretical investigation of the effects of large artificial variations of four rotary stability derivatives on the dynamic lateral stability and control of a 45° sweptback-wing aeroplane model are

NOTE.—*The figures in parenthesis at the end of each Summary are for office use only.*

presented. The experimental results are presented mainly in the form of flight ratings for stability, control, and general flight behaviour. Calculations of period and damping and of the response to rolling and yawing disturbances are also presented.—(1.8.1).

Effect of horizontal-tail span and vertical location on the aerodynamic characteristics of an unswept tail assembly in sideslip. D. R. Riley. N.A.C.A. Report 1171 (1954).

Wind-tunnel results on the effect of horizontal-tail span and vertical location of the horizontal tail relative to the vertical tail on the aerodynamic characteristics of an unswept vertical-tail assembly in sideslip are presented. By applying the discrete-horseshoe-vortex method used for wings to the problem of intersecting surfaces, theoretical span loadings were obtained for each of the configurations tested.—(1.8.1.2).

Aerodynamic forces, moments, and stability derivatives for slender bodies of general cross section. A. H. Sacks. N.A.C.A. Technical Note 3283 (*November* 1954).

Formulae are developed for forces and moments in terms of the body shape and motions, and for stability derivatives in terms of the mapping functions of the cross sections. Relationships are found among the various derivatives, and calculations are made for several configurations. The influence of the squared terms in the pressure relation is demonstrated, and the use of the apparent mass concept is discussed in detail.—(1.8.0.2).

Wings and Aerofoils

See also Compressible Flow

*On the theory of oscillating airfoils of finite span in subsonic flow. W. Eckhaus. N.L.L. Report F.*153 (*published* 1954).

In this report a survey is given of the present state of theories, dealing with the oscillating aerofoil of finite span in incompressible and in compressible subsonic flow. The accuracy and the applicability of these theories is investigated while, in some cases, more rigorous derivations are presented, in order to deepen the insight into the problem.—(1.10.1.2).

*The induced drag due to disturbances in the lift distribution. W. Eckhaus. N.L.L. Report F.*154 (*published* 1954).

An approximate method is presented by which the increase in the induced drag caused by a disturbance in the lift distribution, for some frequently occurring types of disturbances, can rapidly be calculated from graphs. By means of a worked example the good accuracy of the method is illustrated.—(1.10.1.2).

Helicopter Aerodynamics

Preliminary results from flow-field measurements around single and tandem rotors in the Langley full-scale tunnel. H. H. Heyson. N.A.C.A. Technical Note 3242 (*November* 1954).

Measurements of the flow angles and velocities near lifting helicopter rotors, both single and tandem, at a tip-speed ratio of 0·15 are presented and compared with those of theory. The comparison indicates that the theory is sufficiently accurate for use in preliminary design calculations. The flow behind a rotor is shown to be very much like the flow behind a wing.—(1.11.3).

Testing and Instruments

See also Compressible Flow

The theoretical interference velocity on the axis of a two-dimensional wind tunnel with slotted walls. R. C. Tomlinson. A.R.C. Current Paper 181 (*August* 1950, *published* 1954).

A calculation is made of the interference velocity on the axis in the flow of an incompressible fluid past a line doublet in a two-dimensional slotted-wall tunnel, *i.e.* a rectangular tunnel whose shorter sides are slotted in the direction of the flow. The method of analysis is basically the same as that used for cylindrical tunnels by Wright and Ward.—(1.12.1.1).

The efficiency of high-speed wind tunnels of the induction type. A. E. Knowler and D. W. Holder. R. & M. 2448 (*December* 1948, *published* 1954).—(1.12.1.3).

A method of calibrating airspeed installations of airplanes at transonic and supersonic speeds by the use of accelerometer and attitude-angle measurements. J. A. Zalovcik, L. J. Lina and J. P. Trant. N.A.C.A. Report 1145 (1953).

A method is described for calibrating air speed installations on aeroplanes at transonic and supersonic speeds in which use is made of normal and longitudinal accelerations and attitude angle as measured by instruments carried within the aeroplane. An air speed calibration of the pitot-static installation on a jet fighter aeroplane is presented as an experimental check on the accuracy of the method.—(1.12.2 × 13.3).

Liquefaction of air in the Langley 11-*inch hypersonic tunnel. C. H. McLellan and T. W. Williams. N.A.C.A. Technical Note* 3302 (*October* 1954).

Pressure and scattered-light measurements were made in the Langley 11-inch hypersonic tunnel to determine the effect of stagnation temperature on the flow in two Mach number 7 nozzles and to determine the nature of the condensation process occurring at low stagnation temperatures. Liquefaction of the air occurred very close to the saturation point without a condensation shock. The results from varying the water vapour and carbon-dioxide content could not be correlated with Max Volmer's condensation theory.—(1.12.1.3).

AEROELASTICITY

See also Aerodynamics: Loads

An exploratory investigation of some types of aeroelastic instability of open and closed bodies of revolution mounted on slender struts. S. A. Clevenson, E. Widmayer and F. W. Diederich. N.A.C.A. Technical Note 3308 (*November* 1954).

The aeroelastic instability of rigid open and closed bodies of revolution mounted on thin, flexible struts has been investigated experimentally at low speeds. Three types of instability were observed—coupled flutter, divergence, and an uncoupled oscillatory instability which consists in continuous or intermittent small-amplitude yawing oscillations.—(2).

FLIGHT TESTING

A note on the development of sensitive pressure operated water contacts for use on seaplanes. R. Parker. A.R.C. Current Paper 176 (*July* 1952, *published* 1954).

A pressure operated water contact has been developed, suitable for indicating the instants of take-off and touch-down for a seaplane hull. Flight tests have shown that the instrument is accurate in operation and sufficiently robust for normal flight test use.—(13.3).

HYDRODYNAMICS

A survey of scale effects on the hydrodynamic testing of seaplane models. R. Parker. A.R.C. Current Paper 179 (*September* 1953, *published* 1954).

A general survey is made of all the factors where true dynamic similarity cannot be achieved in model tests of seaplane hulls; the likely effects on test results are discussed with reference to towing tank models and medium size research aircraft.—(17.2).

INSTRUMENTS AND EQUIPMENT

Description and preliminary flight investigation of an instrument for detecting subnormal acceleration during take-off. G. J. Morris and L. J. Lina. N.A.C.A. Technical Note 3252 (*November* 1954).

An instrument actuated by longitudinal acceleration and impact pressure has been proposed which would give a quick and easily recognisable quantitative indication of loss in aeroplane acceleration during take-off. A preliminary evaluation from flight tests of a simplified prototype instrument mounted in a jet trainer has been made. The instrument was found to be satisfactory and the response of the indicator to simulated partial power loss was rapid.—(18).